2008-12

The effects of terrain on a system of systems

Ong, Cher Howe.

Monterey, California. Naval Postgraduate School

http://hdl.handle.net/10945/3787

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

THE EFFECTS OF TERRAIN ON
A SYSTEM OF SYSTEMS

by

Cher Howe Ong

December 2008

Thesis Advisor:	Thomas W. Lucas
Second Reader:	Chwee Seng Choo

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2008	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE The Effects of Terrain on a System of Systems			**5. FUNDING NUMBERS**
6. AUTHOR(S) Cher Howe Ong			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE** A
13. ABSTRACT (maximum 200 words) Modern combat operations are predominantly joint or combined arms, in which different forces and weapon systems come together to fight as a single entity—as a system composed of many different systems. For land forces, system of systems typically exists at battalion and above-sized forces. This thesis investigates the effects of two types of terrain (urban and rivers) on combat operations. Using a synthesis of various simulation techniques (rapid scenario generation (RSG), red teaming, experimental design, data analysis, and cluster and outlier analysis), 2,827 of these operations are simulated to understand how the individual systems perform and provide insights into the effects of terrain on battle outcomes. With the operational scenario requiring the simulation of force sizes that were the largest ever attempted (battalion and brigade for the urban and river crossing scenarios, respectively) in Map Aware Nonuniform Automata (MANA, an agent-based simulation environment), an RSG tool was developed. This tool allows future MANA users to easily create combat models at the systems level. Results indicate that both types of terrain are disadvantageous for the attacker, especially the urban terrain. It is found that success in the attack relies critically on the survivability of armor protection, specifically to be able to survive at least three good shots from antiarmor weapons. In addition, for both the defender and attacker, responsive communications was identified as a key determinant of battle outcome and a threshold of less than 1.5 to 2 minutes is required for communications to be effective in enabling effective indirect fires.			
14. SUBJECT TERMS Design of Experiments, System of Systems, Simulation, Network Enabled Warfare, Rapid Scenario Generation, Combat Modeling			**15. NUMBER OF PAGES** 135
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

**THE EFFECTS OF TERRAIN ON
A SYSTEM OF SYSTEMS**

Cher Howe Ong
Captain, Singapore Army
B.Eng (Hons), National University of Singapore, 2003

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

**NAVAL POSTGRADUATE SCHOOL
December 2008**

Author: Cher Howe Ong

Approved by: Thomas W. Lucas
Thesis Advisor

Chwee Seng Choo
Second Reader

James N. Eagle
Chairman, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Modern combat operations are predominantly joint or combined arms, in which different forces and weapon systems come together to fight as a single entity—as a system composed of many different systems. For land forces, system of systems typically exists at battalion and above-sized forces. This thesis investigates the effects of two types of terrain (urban and rivers) on combat operations. Using a synthesis of various simulation techniques (rapid scenario generation (RSG), red teaming, experimental design, data analysis, and cluster and outlier analysis), 2,827 of these operations are simulated to understand how the individual systems perform and provide insights into the effects of terrain on battle outcomes. With the operational scenario requiring the simulation of force sizes that were the largest ever attempted (battalion and brigade for the urban and river crossing scenarios, respectively) in Map Aware Nonuniform Automata (MANA, an agent-based simulation environment), an RSG tool was developed. This tool allows future MANA users to easily create combat models at the systems level. Results indicate that both types of terrain are disadvantageous for the attacker, especially the urban terrain. It is found that success in the attack relies critically on the survivability of armor protection, specifically to be able to survive at least three good shots from antiarmor weapons. In addition, for both the defender and attacker, responsive communications was identified as a key determinant of battle outcome and a threshold of less than 1.5 to 2 minutes is required for communications to be effective in enabling effective indirect fires.

THIS PAGE INTENTIONALLY LEFT BLANK

THESIS DISCLAIMER

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to extend my appreciation to my wife, Siow Wee Han, and daughter, Ong Rui Ting, for their support in the undertaking of this challenging study. Without their unwavering support, it would not have been possible for this study to be completed.

This research started out in International Data Farming Workshop 15 in Singapore, where Professor Lucas (who was lecturing at the National University of Singapore) linked me up with Choo Chwee Seng from DSO National Laboratories, where they had expressed interest in carrying out simulation studies on system of systems. Chwee Seng and his staff from DSO provided model files, materials, and tools (COADM and ART) that served to jumpstart the model-building process in the early stages of the thesis. I would like to thank Chwee Seng for serving as the second reader for this thesis.

I would like to thank Steve Upton, Mary McDonald, Dave Ang, and Chua Ching Lian for providing technical support for data farming runs on the NPS and DSO cluster. Their support proved invaluable in running huge models that take a long time to complete.

I would like to thank Professor Tom Lucas and Colonel Ed Lesnowicz for their advice and supervision in the undertaking of this challenging topic. Colonel Lesnowicz provided valuable operational inputs to ensure that the scenarios are tactically sound and operationally realistic. Professor Lucas provided the simulation and analytic support, which included my attendance at the 16th and 17th International Data Farming Workshops. The advice of both Professor Lucas and Colonel Lesnowicz ensured the quality and relevance of my thesis.

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

This thesis proposes a methodology to study a combat system of systems. It aims to provide decision makers with insights at the systems level on prioritizing scarce resources to support the development of new capabilities. A typical system of systems consists of the following elements: Fire, Maneuver, Mobility/Counter-Mobility, Command, Control, and Communications (C3), Intelligence (I), and Combat Service Support (CSS). For land forces, a system of systems typically exists in battalion and above-sized forces.

In addition, this thesis provides insights into how the various sensors, communications, weapons systems, and forces interact in determining the battle outcome for both the defender and attacker in two types of terrain, namely urban areas and rivers. Both of these pose unique challenges for the attacker and defender. With the increasing urbanization of the world, land forces are expected to be able to conduct combat operations within an urban environment. Urban terrain has the characteristic of being multidimensional, with abundant cover and concealment, along with axes that are dominated by observation and fire from structures along the axes. Moreover, the presence of civilians in the urban environment adds another layer of complexity, where Rules of Engagement (ROE) become important. Rivers have been conventionally a natural line of defense that defending forces exploit to stop the attacking force from advancing. A river crossing operation is a race between the crossing force and the opposing force to mass combat power on the far shore. The longer the crossing force takes to cross, the less likely it will succeed—as the opposing force will defeat the elements split by the river. This thesis is guided by two questions to provide insight into the operational issues to be answered:

- How effective are communications, sensors, weapons, and platforms with regard to enabling the combat system of systems to complete its mission under the two types of scenarios?
- How do the characteristics of the various terrain (urban and rivers) impact the combat forces' performance?

The scenarios have been formulated for the study of combat system-of-systems in these two types of terrain:

- **Urban Operations (UO):** In this scenario, the attacker is a mechanized infantry battalion and the defender is a reinforced company of mechanized infantry. The size of the area of operations is 5km by 5km.
- **River Crossing Operations (RCO):** This scenario consists of an armor brigade minus attempting to secure a breakout point at the far bank of a river. The river is defended by a battalion minus of infantry, reinforced with a company of motorized infantry as reserves. The size of the area of operations is 10km by 10km.

The terrain maps of the two scenarios are shown in Figure 1.

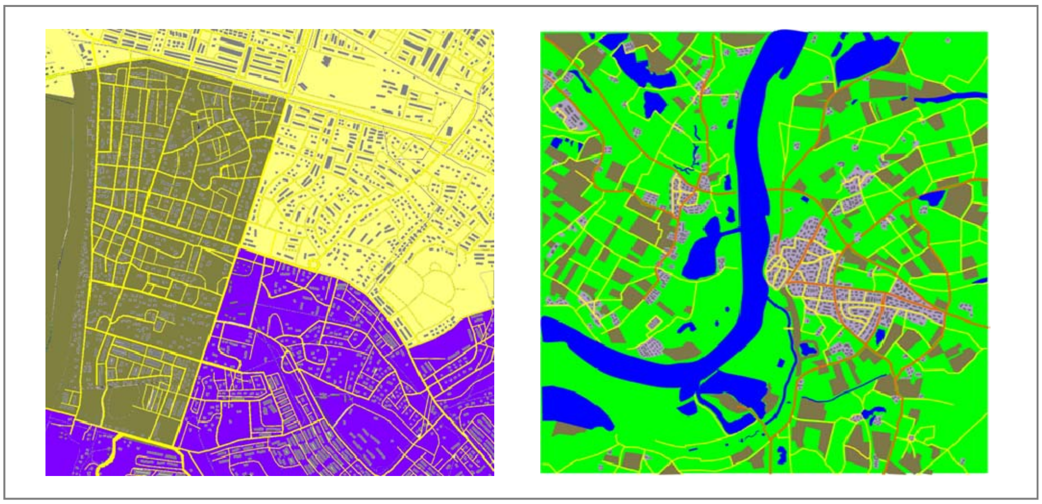


Figure 1. Terrain Maps of the Two Scenarios

In this thesis, a synthesis of different simulation and analysis techniques (Rapid Scenario Generation [RSG], Manual and Automated Red Teaming [ART], Experimental Design and Data Farming, Data Analysis, Cluster and Outlier Analysis for Data Mining [COADM]) were employed to study this complex system of systems. One of the key contributions of this thesis is the development of an RSG tool for the building of very large models in Map Aware Nonuniform Automata (MANA). MANA is a much used stochastic, agent-based combat simulation environment.

Typical agent-based models study up to, at most, company-sized forces; however, the operational scenarios that were studied in this thesis require force sizes of battalion and above. In addition, the complexity of building the combat model increases exponentially as we increase the force size (e.g., company to battalion). Hence, to rapidly scale up the various components of the model (e.g., infantry squads, armor, and artillery detachments) to a battalion and above-sized force, an RSG tool was required. This tool can be used by other MANA users to rapidly scale up their scenario as needed. It allows the rapid building of the model up to any desired size (subject to the limitations of MANA) once the basic building blocks of squad characteristics, communication links, and waypoints are created. In addition, it also enables automation of the design of experiments process. A total of 2,827 of these operations (including both urban and river crossing) were simulated using high-performance computing clusters to generate the data required for the research. The analysis of these data provided answers to the questions posed by this thesis and provided additional insights as well.

With regard to the effects of terrain on performance, results showed that the probability of mission success for the attacker is 26% in the urban scenario and 52% in the river crossing operations, when modeled using a wide spectrum of capabilities and terrain conditions.

We can see that these two types of operations are indeed challenging for the attacker, with only about a 50% chance of success at best. In addition, we see that the urban terrain scenario is more treacherous, compared to that of the river crossing operation, as it is half as likely to succeed. Moreover, both scenarios show that the defender needs to exploit the characteristics of the terrain to his advantage. In urban operations, the cover afforded by the terrain is the key factor, whereas in river crossing operations, concealment afforded by the terrain is more important. This provides us with an important conclusion—that with good concealment afforded by vegetation and overhead foliage in the river crossing scenario, it would be advantageous for the attacker to have sensors that are able to “look” beneath the foliage.

With regard to the effectiveness of communications, sensors, weapons, and platforms, the analysis shows the following:

- **Attacker:** The survivability of armor is critical for success, specifically, armor protection on vehicles should be able to survive at least three good shots (deflect or absorb). This produces a higher casualties for the defender.
- **Attacker:** For targeting of the defender's reserves to be effective, the latency of the sensors in transmitting information back to the shooter has to be less than 1.5 to 2 minutes. If the sensor-shooter latency is higher than that threshold, then it becomes important for the closer range antitank weapons to be effective to take out the defender's reserves. This finding also provided an additional insight in that where the sensor-shooter chain has high latency, the attacker should advance more slowly. This allows the reserves to be deployed in position and then "softened" with fires before the attacker commences capture of the position.
- **Defender:** Communications latency of less than 1.5 to 2 minutes is the identified threshold for reducing defender's casualties. Expanding upon this point, we can conclude that if the attacker is able to jam the defender's communications effectively prior and during the attack, he would be able to blunt one of the defender's few sources of strength.

In addition to insights on the operational scenarios, the thesis also revealed the limits of the MANA model. It was discovered that MANA can handle up to a maximum of around 1,000-plus agents and 2,000-plus communication links. This is the size of the larger river crossing scenario, which involves a brigade-minus force versus a battalion-minus force. A previously-built larger scenario (brigade versus battalion) caused MANA to run out of memory; hence, the scenario was subsequently trimmed down. In addition, the run time for that scenario was around 24 hours per run. Therefore, for a single replicate, it consumes 6,168 hours of computer processing unit (CPU) time, which translates to approximately one week to produce a single replicate.

This thesis demonstrated the synthesis of various simulation techniques to provide answers to operational issues from a system of systems perspective. The analytic results and tools developed can be used to assist decision makers in the development of policies, concept of operations for new systems, and also to evaluate tactics, techniques, and procedures (TTPs).

I. INTRODUCTION

A. OVERVIEW

> It is possible for everybody to buy ships, tanks or airplanes, but the key is how you operate them together in a concept that best suits your operational needs and environment...
>
> RADM(NS) Teo Chee Hean
> Minister of Defense, Singapore
> Opening Address at Singapore Armed Forces (SAF) Centre for Military Experimentation (SCME) 29 Dec 2003
> (Defense Science Technology Agency, 2003)

Modern warfare is characterized by the use of combined arms, where various types of forces (e.g., combat, combat support, and combat service support) with different weapon systems and equipment come together to fight as a single entity — as a combat system of systems. Figure 2 shows how the various elements of a system of systems interact.

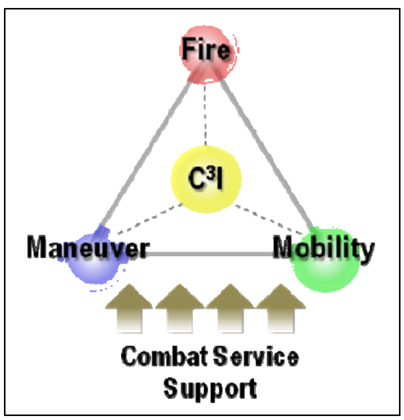


Figure 2. System of Systems

A typical system of systems consists of the following components:

- **Fire:** This is ultimately what a combat force delivers onto its opponents to attrite them and win the battle. Fire can come in two forms—direct fire and indirect fire. Direct fire is defined as fires that are delivered with a straight trajectory, with a direct line-of-sight to the target. These include small arms fire (e.g., M16, AK47, etc.), tank rounds, and antitank weapons. Indirect fire is delivered with weapons that do not require direct aim at the target (e.g., artillery guns, precision guided missiles, and close air strikes).

- **Maneuver:** These are the forces that engage in direct combat with the opponent. They include forces like infantry and armor. The forces in this component maneuver to deliver fire on the enemy so as to be able to suppress the enemy and maneuver.
- **Mobility:** Opposing sides will seek to impede the ability of their enemy by exploiting the natural features of the terrain and by creating obstacles to slow the advance of the opponent. This will disrupt the opponent's ability to mass his combat power and provide opportunities for fire to be delivered to attrite him. In this aspect, the combat engineers provide the capability for enhancing the mobility of our own force by breaching obstacles and emplacing obstacles to impede the mobility of the enemy.
- **Command, Control, and Communications, Intelligence (C3I):** This is the component that synthesizes the elements of fire, maneuver, and mobility together. It is here where the information from sensors emplaced within the battlefield is fused and disseminated to the combat units through the various communication links.
- **Combat Service Support (CSS):** The combat force needs to be adequately resupplied between battles. CSS comes in five main components: manpower, material, maintenance, movement, and medical. In this study, CSS is excluded as each of the scenarios consists of only one major battle.

B. BACKGROUND AND MOTIVATION

1. Urban Terrain – A Multidimensional Battlefield

> Army forces will likely conduct operations in and around urban areas—not as a matter of fate, but as a deliberate choice linked to national objectives and strategy and at a time, place, and method of the commander's choosing.
>
> FM 3-06, *Urban Operations* (Headquarters, Department of the Army, 2003)

As a consequence of global urbanization, a trend of migration from rural to urban areas is occurring throughout the world. Coupled with the exponential increase in world population, massive urban areas hold the centers of population as people move from rural to urban areas. It is estimated that almost half the world's population resides in cities and urban areas (Headquarters, Department of the Army, 2003).

The urban terrain consists of natural and man-made features, with man-made features being the major part. Buildings, streets, and other infrastructure within the urban terrain have very different patterns, shapes, and sizes. The infinitely many ways in which these factors can interact with one another make it difficult to describe a "typical" urban area. Figure 3 shows the complexity of the urban battlefield.

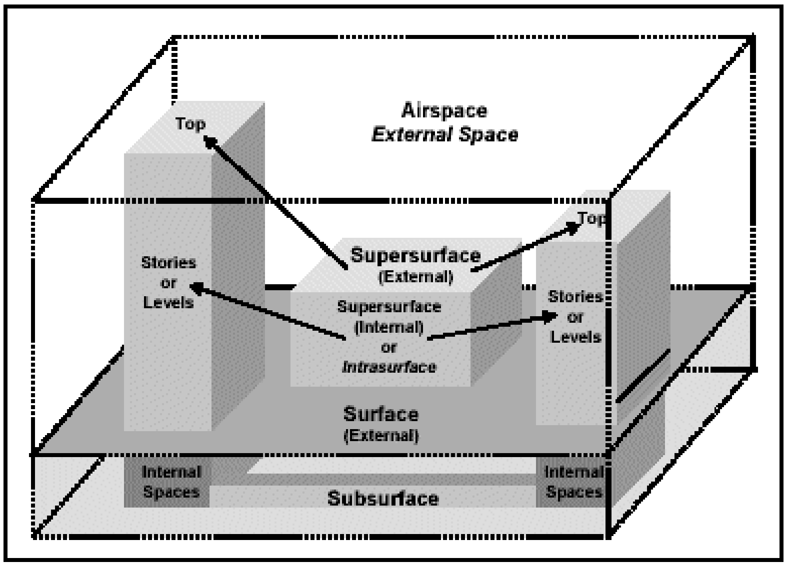


Figure 3. Multidimensional Nature of the Urban Battlefield
(From Headquarters, Department of the Army, 2003)

An urban area may appear relatively insignificant on a map as compared to the surrounding countryside. The truth is, in fact, the reverse, where the size and extent of the urban battlefield is many times that of a similarly-sized piece of the natural terrain. The sheer volume and density, as a result of the complex urban geometry and dimensions, can make urban operations highly resource-intensive in terms of time, manpower, and material.

2. Rivers – A Natural Defense Line

> A river crossing is a race between the crossing force and the enemy to mass combat power on the far shore. The longer the force takes to cross, the less likely it will succeed, as the enemy will defeat, in detail, the elements split by the river. Speed is so important to crossing success that extraordinary measures are justified to maintain it.
>
> FM 90-13, *River Crossing Operations*
> (Headquarters, Department of the Army, 1998)

The purpose of any river crossing operation is to project combat power across a water obstacle to accomplish a mission. A river crossing operation is unique in that it requires detailed and careful planning. It also requires well-orchestrated, combined arms operations to ensure a successful crossing of the river. There are four major phases in a river crossing operation (Headquarters, Department of the Army, 1998).

- **Advance to the River (Phase I):** This requires the crossing force to attack to capture and secure near-shore terrain, such as favourable road networks and crossing sites.
- **Assault Across the River (Phase II):** The purpose of this phase is to rapidly project combat power on the far shore to eliminate the enemy's direct fire onto the crossing sites and secure terrain for attack positions. This will facilitate the crossing of follow-on forces for the subsequent phases.
- **Advance From the Exit Bank (Phase III):** Once the follow-on forces have crossed the river, elimination of any remaining direct or indirect fire from the crossing area will be carried out in this phase.
- **Secure the Bridgehead (Phase IV):** The bridgehead must be defendable and large enough to accommodate the reorganization of forces that will break out to continue offensive combat operations beyond the bridgehead line. This includes securing of construction points created by the terrain to hold off any counterattack by the incumbent.

Throughout history, armies have crossed rivers to pursue or retreat from enemy forces. The ancient Persian Army built bridges during their invasion of Greece in the fifth century BC. In 480 BC, the army of Xerxes commenced preparations to cross the Hellespont, the narrow strait in Turkey that separates Asia from Europe. This was a colossal challenge even by today's standards, for the bridge had to be over a mile long.

Two attempts were made to construct the bridge, as the boat bridge was broken up by strong winds and waves in the first attempt. Eventually, the entire Persian Army (said to number a million men) crossed it.

More recently, in World War II, was the crossing of the Rhine River, which represented Germany's resolve at holding off Allied forces on the Western front. The successful crossing of the Rhine River was one of the key turning points in the battle for Germany. Figure 4 shows the attack plan of the Allied Forces.

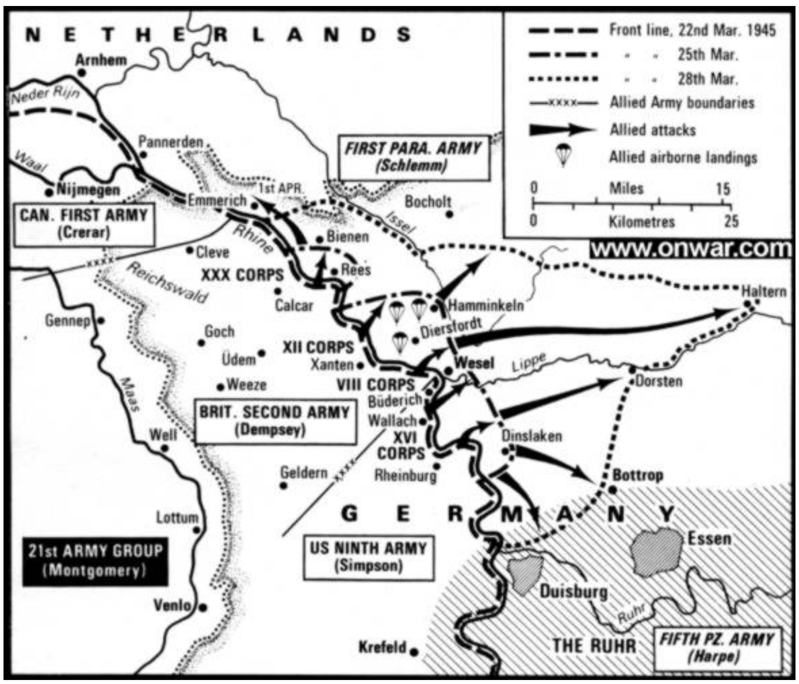


Figure 4. Crossing of the Rhine River
(From Allied Crossings of the Rhine North of the Ruhr)

Operation Plunder was carried out on the night of 23 March 1945. It involved the crossing of the Rhine River at Rees, Wesel, and south of the Lippe Canal by the British Second Army, and the U.S. Ninth Army. The XVIII U.S. Airborne Corps, consisting of the British 6th Airborne Division and the U.S. 17th Airborne Division, conducted Operation Varsity to insert forces across the Rhine River to secure critical terrain ahead of the main force so as to maintain the momentum of the advance.

3. Motivation

In designing new force structures to meet current and future operational requirements, a systems perspective of the operational environment (Joint Chiefs of Staff, 2006) is fundamental. A systems perspective considers more than just an adversary's military capabilities; it strives to provide an understanding of the interrelated systems of both its own forces and the enemy interacting with the operational environment relevant to an operation.

Studying battalion-sized and above forces can be especially difficult in live environments, as they require large numbers of personnel, including control personnel, and safety setup. In addition, "noise" present in the data set cannot be easily isolated. Although constructive war-gaming exercises can cut down on the number of live troops participating, it still requires a significant involvement of military planners to "man" the simulation and exercise control personnel to take data for after-action reviews (AARs). Moreover, the number of data points and factors that can be varied for subsequent study is severely limited by time and resources. Very often, only a handful of data points can be extracted, which does not provide for a robust and holistic analysis of the entire combat force. In order to better understand how the individual systems interact with each other to produce a battle outcome, the individual factors of the various systems have to be varied systematically to ensure that one can carry out an analysis.

With agent-based simulations, the study can be "unmanned" and allow for many more factors to be varied for an in-depth study to be carried out. This does not imply that agent-based simulations are a replacement for war-gaming and live exercises. Agent-based simulations can provide an initial understanding of the entire combat system and allow us to focus on key operational issues that matter, before carrying out live exercises. This is especially useful during the design stage of new force structures, where the actual systems are not even present.

In addition, without highly automated tools to assist in the generation of the model and extraction of data for analysis, the modeling of large-scale combat scenarios can be time-consuming and tedious. Manual generation of models and analysis can be

prone to error as a result of analyst fatigue. This may result in a less than robust analysis of the problem at hand. Hence, RSG and analytic tools need to be developed so that such complex systems can be modeled and analyzed with ease.

C. RESEARCH QUESTIONS

The aim of this thesis is to analyse the system-of-systems in an urban and river crossing operational scenario. The following questions guide this research:

- How effective are communications, sensors, weapons, and platforms with regard to enabling the combat system-of-systems to complete its mission under the two types of scenarios?
- How do the characteristics of the various terrain (e.g, urban and rivers) impact the performance of the combat forces?

D. BENEFITS OF THE STUDY

This study demonstrates the tools and framework that can be used for analyzing a system-of-systems, not limited just to land forces, but possibly including air and sea forces as well. In addition, this study provides insights into how the capabilities of the individual combat systems (tanks, rifles, infantry fighting vehicles) influence the final battle outcome. Ultimately, this thesis provides an understanding of the challenges and limitations of operating in the two unique terrain types.

E. RESEARCH METHODOLOGY

The tool used in this study is an agent-based distillation. It is a type of computer simulation that models only the salient features of the real world and not every possible characteristic (Cioppa, Lucas, & Sanchez, 2004). The tool used is Map Aware Nonuniform Automata (MANA), a product developed by New Zealand’s Defense Technology Agency (DTA). Scenarios for both terrain features (urban and rivers) are then developed for experimentation in MANA.

Data farming then identifies the previously undetermined characteristics and situations that develop during the simulation (Cioppa, Lucas, & Sanchez, 2004). Statistical analysis and other analytic techniques identify the importance of the interactions between variables and lead to an understanding of the data.

In order to identify a scenario that is most threatening to the BLUE forces, the Automated Red Teaming (ART) (Choo, Chua, & Tay, 2007) technique is explored to search for possible RED deployment of reserve forces that can tilt the battle in RED's favor.

II. SCENARIO AND MODEL DEVELOPMENT

A. INTRODUCTION

In order to capture the essence of how a system-of-systems conducts operations in both urban and river terrain, it is essential that robust and realistic scenarios are properly developed. In this chapter, the structure of the forces, and a brief description of the scenario, is covered. In addition, an overview of the MANA simulation tool that is used to model the combat scenarios is provided. Lastly, this chapter describes in detail how the simulation model behaves. Both scenarios were validated by Colonel Edward Lesnowiz, United Sates Marine Corps (Ret.) to confirm that they are operationally realistic and tactically sound.

B. SCENARIO

1. Urban Operations (UO) Scenario

a. Terrain Model

The terrain model for the urban terrain used in this scenario was developed by the Defense Science Organization (DSO), Singapore, in a UO study that was presented during the International Data Farming Workshop 15 (Team 7 - Applying Automated Red Teaming in an Urbans Operations Scenario, 2007). It is a map size of 5km by 5km. The map is as depicted in Figure 5.

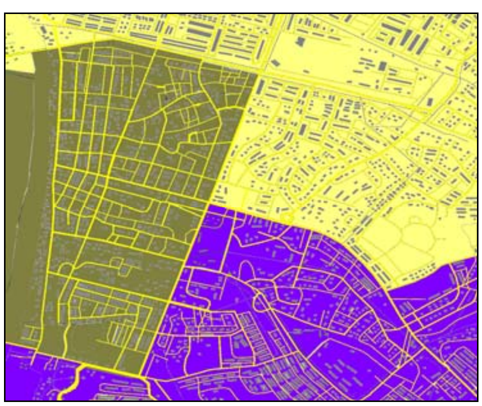


Figure 5. Scenario Map of the Urban Operations Model (From: Team 7 - Applying Automated Red Teaming in an Urbans Operations Scenario, 2007)

b. Force Structure

The attacker modeled in the UO scenario is a mechanized infantry (MI) battalion, structured as follows:

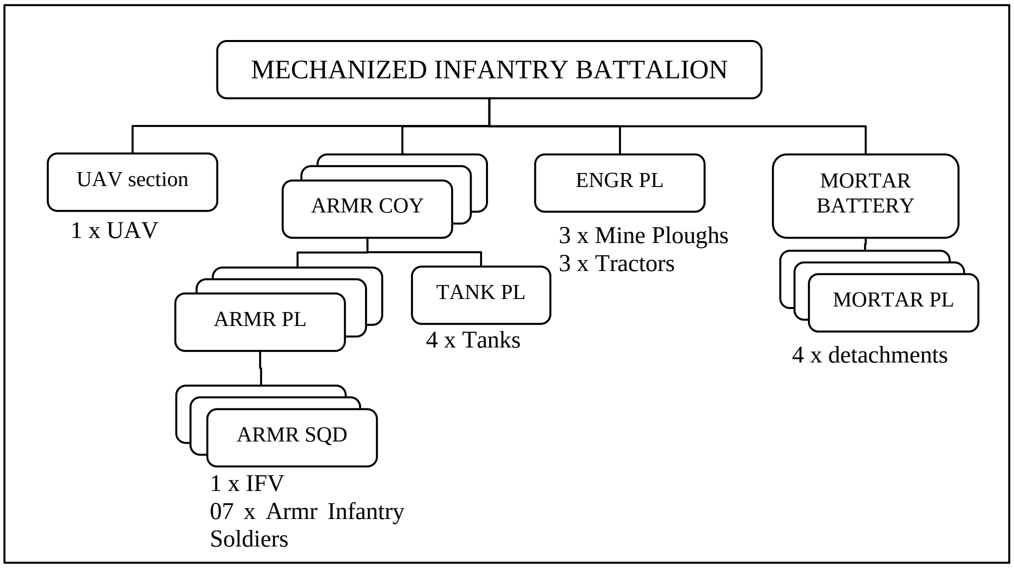


Figure 6. Structure of Attacking Force in an Urban Operations Scenario

The defender modeled in the UO scenario is a reinforced mechanized infantry (MI) company deployed in the area of operations (AO).

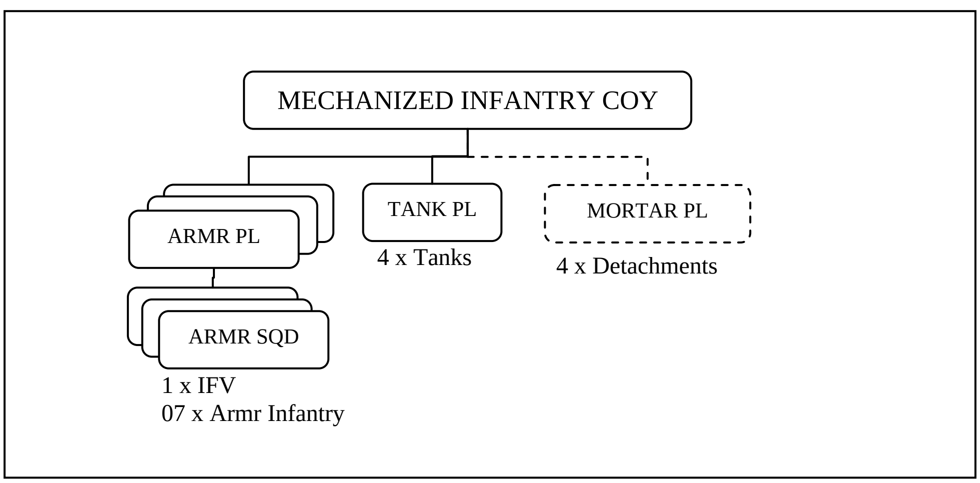


Figure 7. Structure of Defending Force in an Urban Operations Scenario

c. Scenario

Defender's (RED) Basic Deployment: At the security area, obstacles such as mine clusters, improvised explosive devices (IEDs), and roadblocks are established to cause maximum delay and to disrupt to the attacker's advance to allow more time for the defender's indirect fire to attrite the attacker's forces. The defender deploys a section and a mechanized infantry platoon minus along each axis. The tank platoon is organized into two teams of two tanks each to reinforce the eastern and central axes. The defender holds a reserve of a mechanized infantry company minus at the rear of the area of operations. The reserves are deployed in two echelons, each consisting of a mechanized infantry platoon and a tank team. Each of the reserves will immediately reinforce the forward positions where the defenses are being breached. A pictorial representation of the basic deployment and deployment of reserves is shown in Figure 8.

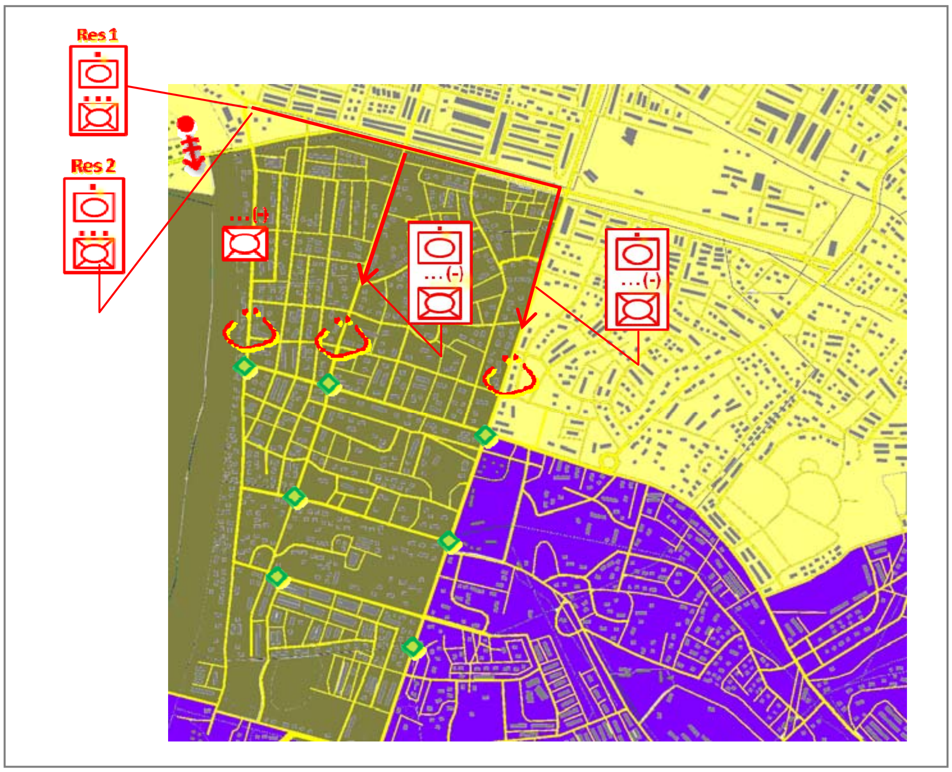


Figure 8. Urban Operations Model Defender Operations Plan(Best Viewed in Color) (After: Team 7 - Applying Automated Red Teaming in an Urbans Operations Scenario, 2007)

Attacker's (BLUE) Concept of Operations: The attacker's mission is to open at least one axis through the AO. A platoon is first inserted to the rear to establish a blocking position to stop the defender's reserves from reinforcing the attacked frontal positions. The self-propelled howitzers (SPHs) are held at the rear to provide support fire to the advancing troops. The attacker then advances along two main axes, each with a task force consisting of one mechanized infantry company and one engineer section each, holding a task force in reserve. The reserve task force is employed to rush through whichever axis is opened successfully. Figure 9 shows the operations plan of the attacker.

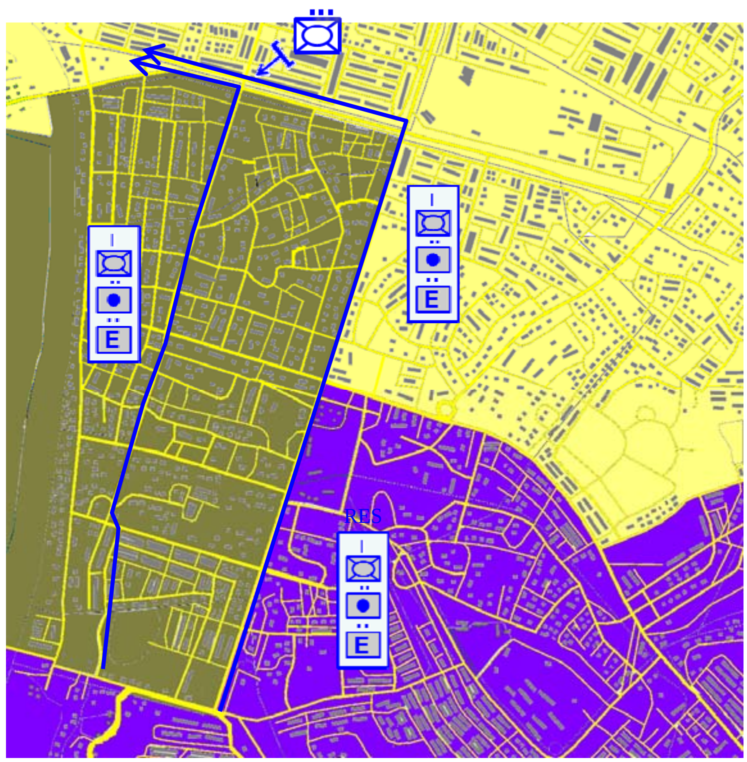


Figure 9. Urban Operations Model Attacker's Operations Plan(Best Viewed in Color) (After: Team 7 - Applying Automated Red Teaming in an Urbans Operations Scenario, 2007)

2. River Crossing Operation (RCO) Scenario

a. Terrain Model

The terrain selected for this scenario is based upon the World War II crossing of the Rhine River at Rees. The map is extracted from Google Earth and modeled using photo editing software. In Figure 10, we see the image on the left as the map extracted from Google Earth and on the right is the one that has been rendered for use by the simulation model.

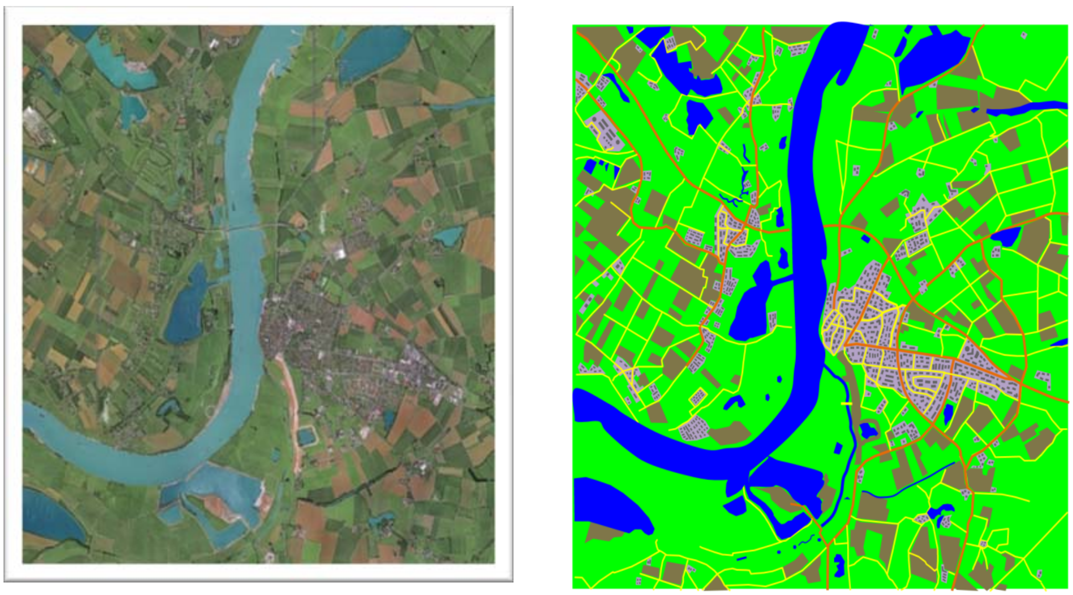


Figure 10. River Crossing Operation Scenario Map (Best Viewed in Color) (From: Google Earth, 2008)

b. Force Structure

The attacker in the RCO scenario is a mechanized infantry brigade reinforced with a bridge company to support the initial crossing and a field artillery battalion to provide additional fire support to the crossing effort. The structure of the mechanized infantry(MI) brigade is shown in Figure 11.

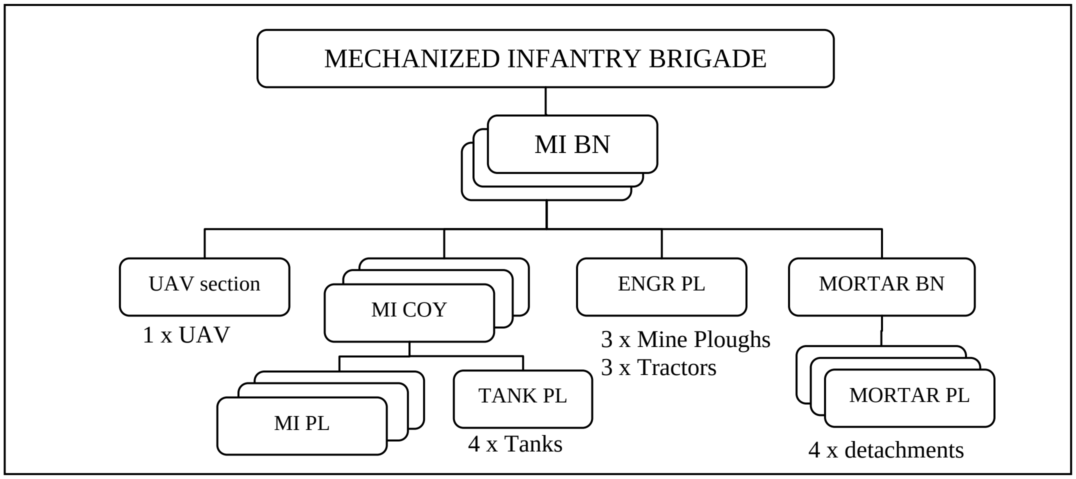


Figure 11. River Crossing Operation Model Attacker Force Structure

The structure of the bridge company and the field artillery battalion is shown in Figure 12.

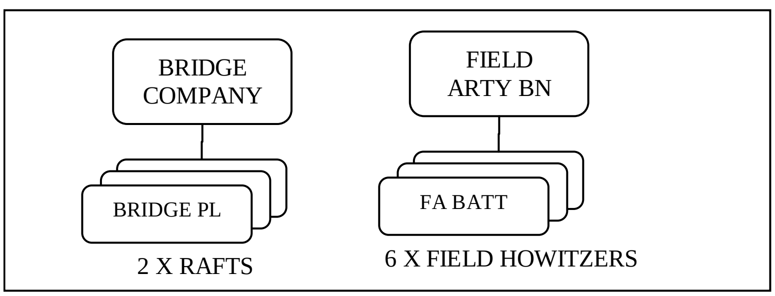


Figure 12. River Crossing Operation Model Attacker Support Forces Structure

The defender forces that are modeled consist of a reinforced infantry battalion with the structure shown in Figure 13.

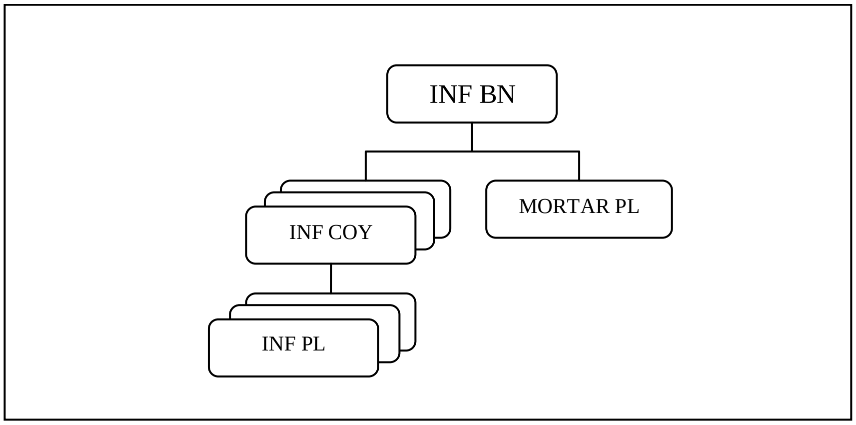


Figure 13. River Crossing Operation Model Defender Force Structure

As a result of computer and software memory limitations, however, the maximum size force that can be modeled is an armored brigade minus (two battalions) against an infantry battalion minus (two companies).

c. Scenario

Defender (RED) Basic Deployment: RED will deploy their forces with two companies to the front and one company to the rear, holding a motorized infantry platoon as the battalion reserve, with an additional armored infantry company to be reinforced by the parent brigade if required. At the forward of the main defense area along the river, a platoon will be deployed to dominate each of the crossing sites. Obstacles are manned and kept open along the key reinforcement routes. Upon commencement of attack on the forward positions, the battalion reserve will be launched to reinforce the positions that are being attacked. The company-sized brigade reserve will be launched upon commencement of attack on the forward positions. This defense is supported by two batteries of artillery equipped with counterbattery radar. The schematic of how the defender is deployed is shown in Figure 14 (note that the greyed elements indicate the forces that are not modeled as a result of model limitations in MANA).

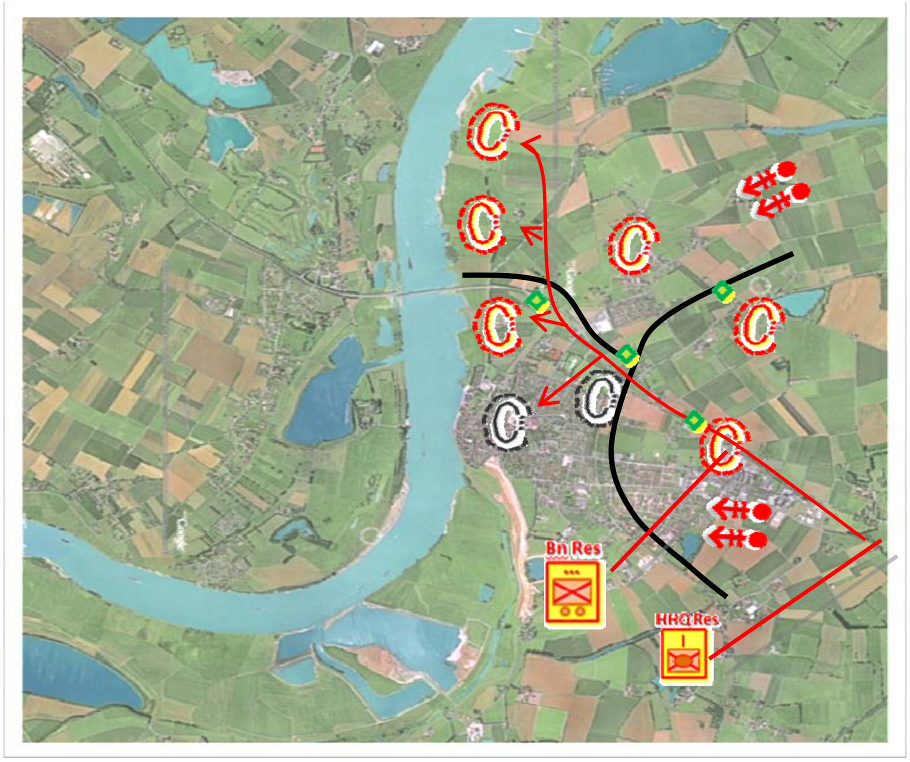


Figure 14. River Crossing Operation Model Defender's Operations Plan (Best Viewed in Color) (After: Google Earth, 2008)

Attacker (BLUE) Concept of Operations: The attacker will insert a company-sized force to the rear of the area of operations to attrite the reinforcements and prevent them from reinforcing the frontal positions. With the support of heavy artillery fire from a division artillery battalion to suppress the frontal objectives, as well as provide counterbattery fire against the defender's artillery, the attack commences with an assault crossing of an armored battalion across the Rhine River. This is followed by the capture of the objectives directly dominating the crossing sites. Upon capture of the frontal objectives, the rest of the brigade, consisting of two battalions, is ferried across the river to secure the bridgehead to the depth of the area of operations. Figure 15 shows the operations plan of the attacker.

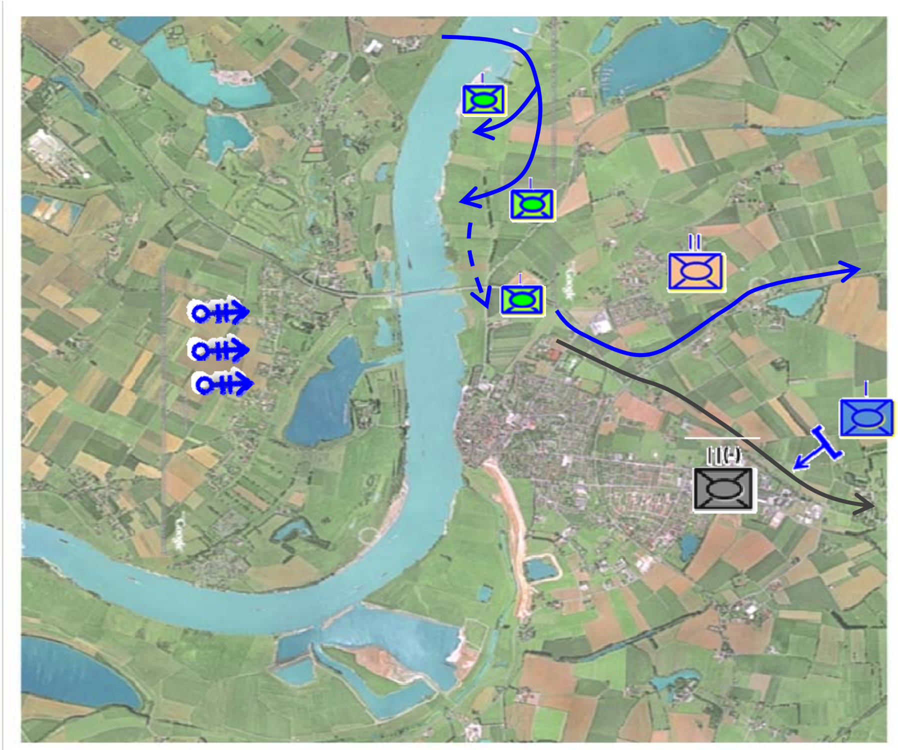


Figure 15. River Crossing Operation Model Attacker's Operations Plan (Best Viewed in Color) (After: Google Earth, 2008)

C. THE MANA COMBAT SIMULATION TOOL

Having described the scenarios, this section describes the combat simulation tool. The tool used is an agent-based simulation tool called MANA. It is selected as the modeling tool best suited for this research. This section briefly covers how the tool works.

1. MANA Characteristics

MANA is in a general class of models called agent-based models (ABMs). ABMs have the characteristic of containing entities that are controlled by decision-making algorithms. MANA was built by New Zealand's DTA for research into the complex and chaotic nature of real-world combat situations and to provide users with insights into those same situations. It employs the use of individual entities that are able to make decisions based upon certain rule sets that are assigned to them to explore the essence of

a given operational issue (McIntosh, Galligan, Anderson, & Lauren, 2007). This independent decision-making ability is possible with the provision of individual situation awareness maps as well as the agent's personality. Its primary use is as a "distillation" tool; that is, to create a bottom-up abstraction of a scenario that captures just the essence of a situation, and leaves out details that are not essential.

D. CHARACTERISTICS OF THE SIMULATION MODEL

The aim of this section is to describe the characteristics of the MANA models created for this research. The goals of the simulation, terrain and scale, and enemy and friendly forces are discussed here. In addition, the sources of data and assumptions are also addressed. A more detailed breakdown of the behavioral characteristics and capabilities of all the forces can be found in Appendix B.

1. Simulation Goal

The scenarios developed are designed to provide a better understanding of the challenges of operating in the two types of terrain and to gain insights into how the myriad of factors in a combat situation interact with one another. In this simulation study, the factors that are varied are capability and environment focused. That is, factors which relate to force and equipment effectiveness (e.g., probability of hits, speed, armor) and also to the environment in which they operate in (e.g., cover and concealment, civilian density). These factors are varied using design of experiments techniques and explored over large ranges to determine how they interact and to determine the factors that are important and at what levels.

2. Terrain and Scale

a. Scale

MANA is essentially a time-step model that requires the user to match the real-world scales to those used in the simulation. In this simulation, the time scale is coupled one-to-one with that of the real world. That is, one time step is equivalent to one second. The scale of the terrain maps for the two scenarios is shown in Table 1.

Scenario	Real-World Size (km)	MANA Size (pixels)	Scale
Urban Operations	5 x 5	500 x 500	1 pixel: 10m
River Crossing	10 x10	1000 x 1000	1 pixel: 10m

Table 1. Scale of Terrain Maps in the UO and RCO scenarios

b. Terrain Map

MANA allows for various types of terrain to be modeled, which includes walls, buildings, bushes, and water. Three attributes of cover, concealment, and going of various types of terrain are modeled. These attributes take on values between 0 and 1 and are described as follows:

- **Cover** relates to the amount of protection that an individual agent receives when he is being fired upon; the higher this attribute is, the less likely the agent will be hit while being shot at by an enemy agent.
- **Concealment** relates to the amount of camouflage the terrain offer agents which reduces their detectability by enemy agents.
- **Going** describes the mobility offered by the terrain and relates to how fast an individual agent can move through the terrain. By setting this to zero, it becomes impassable terrain for the agent and this can be set for terrain types like walls and rivers.

The terrains modeled in the two scenarios are listed in Table 2.

S/N	Scenario	Terrain	Going	Cover	Concealment
1.	Urban Operations	Industrial	0.10	0.20	0.50
		Building	0.10	0.90	0.90
		Road	1.00	0.00	0.00
2.	River Crossing	River	0.00	0.00	0.00
		Light Bush	0.50	0.10	0.30
		Buildings	0.10	0.90	0.90
		Urban	0.20	0.60	0.70
		Cleared Land	1.00	0.00	0.00
		Road	0.80	0.00	0.00
		Highway	1.00	0.00	0.00
		Crossing Sites	0.50	0.00	0.00

Table 2. Terrain Information (Going, Cover, and Concealment)

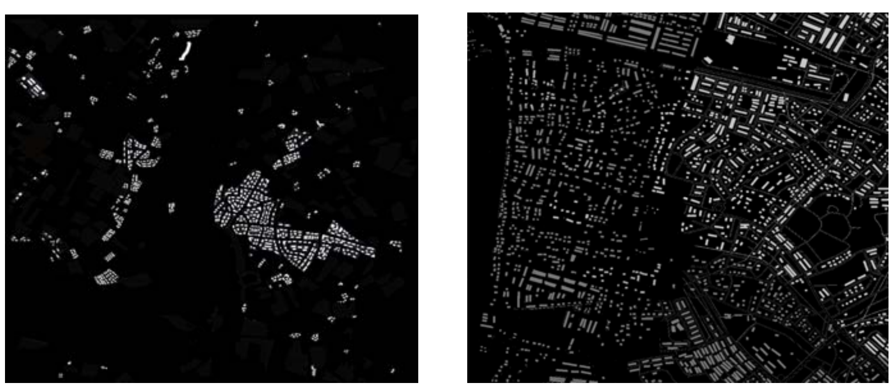
The terrain maps are shown in Figure 16.

River Crossing Scenario Terrain Map ***Urban Ops Scenario Terrain Map***

Figure 16. Terrain Maps (Best Viewed in Color) (After: Google Earth, 2008 and Team 7 - Applying Automated Red Teaming in an Urbans Operations Scenario, 2007)

c. Elevation Map

To provide for a three-dimensional battlefield where different elevations affect forces' line-of-sight, the elevation of the battlefield can also be specified via a greyscale bitmap file of the terrain map. The darker shades indicate those areas that are of lower elevation, whereas those that are of lighter shades correspond to that of higher elevations. The elevation maps of both the river crossing operation scenario and that of the urban operations scenario are shown in Figure 17.



River Crossing Scenario Elevation Map ***Urban Ops Scenario Elevation Map***

Figure 17. Elevation Maps (After: Google Earth, 2008 and Team 7 - Applying Automated Red Teaming in an Urbans Operations Scenario, 2007)

The elevation that is modeled in these two scenarios predominantly consists of buildings and urban areas.

3. Classes of Agents

In both models, there are three classes of agents: obstacles, human, and vehicular agents. They are given threat classifications of I, II, and III, respectively. Obstacle agents model the effects of obstacles on the battlefield, which is to stop the opposing force from advancing. The obstacles have no effect on human agents since in reality obstacles are not effective in stopping infantry troops, and they are primarily employed to stop vehicles. Human agents can consist of civilians, infantry troops, and also mechanized infantry troops. Depending upon their type, they may or may not carry weapons. Vehicular agents are a broad class of agents consisting of armored vehicles, artillery, rafts, etc. These agents can have the ability to carry passengers. However, as a result of limitations in MANA, the agents will only be able to embuss and de-embuss the vehicular agent once.

4. Generic Behavior of Forces

This section describes the general characteristics of the forces that are modeled. In terms of rules of engagement (ROE), they will not engage any forces if it is likely to result in casualties to civilians or neutrals. With the exception of infantry agents, all agents who encounter an enemy obstacle agent will be stopped. This is achieved using the refuel option, where an agent that is being refueled by the enemy obstacle agent will not be able to move until the obstacle agent is cleared. In addition, all forces will slow down when they come into contact with an enemy force, either visually or when they are being shot at.

5. Modeling of Weapons

In order to reflect a more accurate reality that the closer the target the higher the probability of hit, a simple triangular range-hit probability distribution is employed. At the maximum effective range of the weapon, the probability of hit is taken as zero. In addition, if the weapon has a minimum distance for engagement (to account for arming

distance of rounds), the hit probability will be zero until the minimum effective range, where a probability of hit is assigned. The model is shown in Figure 18.

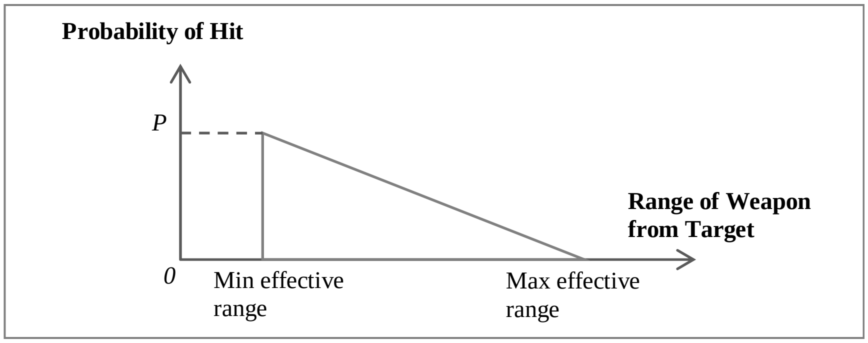


Figure 18. Model of Weapon Probability of Hit

6. Sources, Abstractions, and Assumptions

The probabilities of hits and ranges of weapons modeled are referenced from (Sulewski, 2005). In that study, an extensive research on the characteristics and capabilities of many weapons was carried out. This included weapons from small arms to antitank weapons to artillery weapons.

In both of the scenarios, CSS (which covers manpower replacement), material resupply (fuel, food, water, etc.), maintenance issues (e.g., failure of equipment), and medical evacuation are not considered. One of the reasons is that CSS becomes critical when there are multiple sequential missions within the scenario, where resupply becomes important in bringing up the readiness level of the force for the next mission. There is only one mission to be completed in both scenarios; hence, CSS is not modeled in this thesis.

7. Bugs

To model the effect of inaccurate information, the contact position uncertainty parameter was explored. The intended effect was to introduce an uncertainty in the information that will be transmitted among friendly forces. This was done to understand the impact on the MOEs when accurate communication cannot be carried out on the

battlefield. One of the key effects was to see if accurate coordinates calling for artillery fire matters and, if so, by how much. However, with the use of this parameter problems may occur when the enemy unit to be fired upon is located close the edge of the battlefield. Therefore, a position uncertainty may cause a coordinate that is outside of the defined battlefield grids to be transmitted to the shooter. This will unwittingly cause MANA to crash.

E. RAPID SCENARIO GENERATION (RSG) TOOL

1. Motivation

One of the key challenges of analyzing system of systems is in the building of the model and setting it up for analysis. Within a system-of-systems, there are many force types, each with its own characteristics (weapons, behavior), mission (in terms of waypoints), and communication links. These characteristics are repeated in one way or another across the entire system. In order to be able to generate the large numbers of squads of agents, as well as the numerous communications links, easily within the system, an RSG tool is required.

2. Concept of Tool

A particular agent or squad has three unique characteristics that define them: generic force type, waypoints, and communication links. Each of these characteristics will be described in detail.

a. Generic Force Type

This describes the type of agent or squad it belongs to (e.g., mechanized infantry, tank, or artillery). Each of these force types have their own behavioral characteristics in accordance to its known TTPs, in which case, we will refer to them as the personality within the context of MANA. In addition, each force type will also have their individual weapon and sensor assignments that differ from the rest. For instance, the primary weapon that an artillery unit has is very different from that of an infantry soldier.

b. Waypoints

The various force types can come together to form a unit. This unit will have routes (or waypoints in MANA) in the given AO that it has to take to complete a given mission. These routes will then have to be taken by the various force types that come under the command of the unit.

c. Communications Links

In order for the agents to pass information among the various force types within a unit, communications links have to be set up between them. Generally, the communications links can be in the form of two-way, where the agents communicate, or one-way, where the agents just use the situational awareness (SA) information relayed to them to carry out the mission. Each of these communications links have their individual characteristics, such as range of communications, time in which information takes to be passed through, and the type of information that is relayed (positions of enemy, own, and neutral forces).

The combination of these three characteristics produces a unique squad with its own force type, waypoints corresponding to that of its parent unit, and how information is relayed between itself and the other squads.

3. Implementation of Rapid Scenario Generation (RSG)

The RSG tool is created in Excel and is programmed using Visual Basic for Applications (VBA). Excel is chosen as the tool of choice because of its ease in carrying out “copy-and-paste” operations. This is especially helpful where multiple units can be easily replicated by simply copying and pasting the particular rows and columns. Exploiting the characteristics of the MANA model file, which is in the Extensible Markup Language (XML), this tool extracts the characteristics required from each of the squads modeled, such as communications links, waypoints, or squad type, in the form of text and then reassembles all the lines of text back into one coherent scenario. The process for generating a scenario is as follows.

- Scenario files are created separately each for generic force types, waypoints, and communication links in MANA. The squads in each of these scenarios are then saved out and imported into the Excel RSG tool. The user will have to create a base scenario as well, one that is empty of squads. This base scenario file will specify the terrain maps, the terrain type, output file settings, etc. All generated squads will be loaded into this base scenario file.
- Within the Excel RSG tool, the user specifies the name of the squad he wishes to create and assigns the force type, the waypoints to be used, and the communications links to be generated.
- With the click of a button, with user-provided inputs, the scenario will be generated.

Appendix A consists of detailed instructions on how to use the RSG tool. A diagrammatic flowchart, showing how the RSG tool is implemented, is shown in Figure 19.

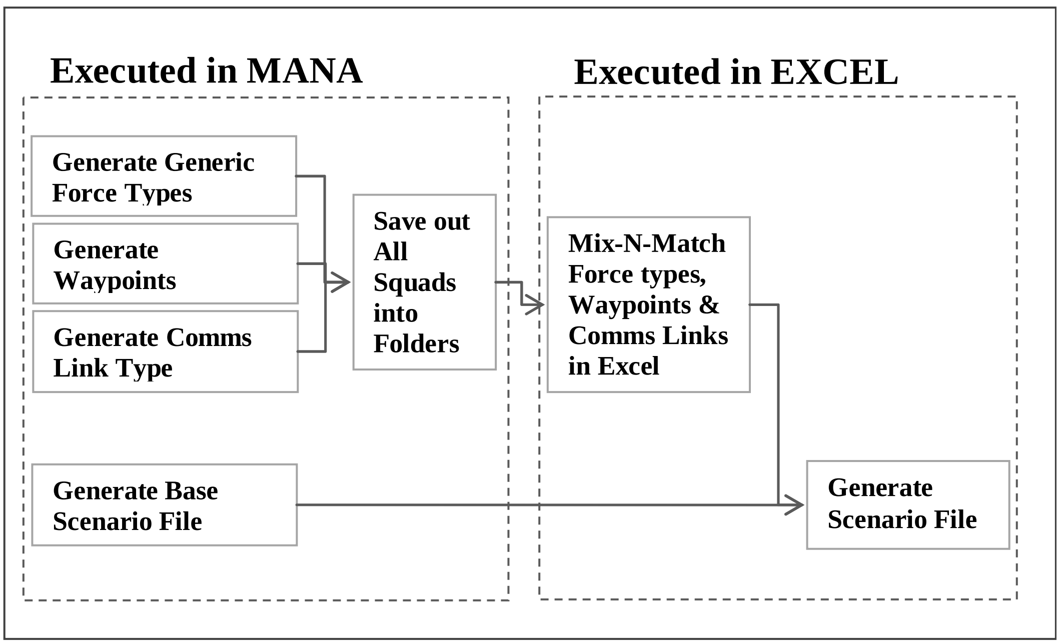


Figure 19. Architecture of Rapid Scenario Generation Tool

4. Upper Limits on the Processing Capability of MANA

As this tool is able to rapidly populate forces for the scenario, resulting in thousands of agents and communications links created within minutes, the upper limit on the number agents that MANA can process was reached, as it throws an out-of-memory exception. The developers of MANA (Galligan, 2008) provided an upper limit on the program's processing capabilities with the following parameters:

```
CONSTANTS:
   Num_MultiRuns = 100000;
   Num_Steps = 100000;
   Num_States = 59;
   Num_Wpn = 6; // Number of weapons allowed
   Num_Sens = 6; // Number of sensors allowed
   Num_MOE = 5;
   Num_Wgts = 32;
   Num_Ranges = 77;
   Num_Tags = 326;
   Num_Start_Tags = 14;
   Num_End_Tags = 15;
   Num_TabVal = 30;    // Number of Sensor/Sskp/Target AgtClass/Non
Targets accepted in table
    Max_WPs = 100;
    Max_Homes = 100;
    Max_RecAgts = 999;
    Max_Integer = 2147483647;
    Num_BuiltinTerrains = 6;
```

One of the key issues with managing huge models is the need to be prudent with the use of memory. One of the important factors was communications links and, in particular, the queue buffer size. This is the number of messages that can queue up when the capacity of the communications link is reached. By default, MANA sets the queue buffer size to infinity. In order to ensure that the thousands of communications links do not consume all the memory, there is a need to set this to a finite number.

Other than the communications links' characteristics, it is also important to design the communications topology to ensure that the memory is efficiently used. If there is a

need for multiple squads within a unit to communicate among each other, in a small scenario the many-many topology can be used, since memory is not likely to be an issue. However, in a large scenario with many communications links, a more preferred topology would be many-one-many. This involves the creation of a dummy relay agent that relays the messages. Figure 20 shows the difference between the two types of topology. We can see that for the many-many communications topology, the complexity of the communications grows in $O(n^2)$, in polynomial order two rate, whereas in the many-one-many topology, it grows in a linear rate of $O(n)$.

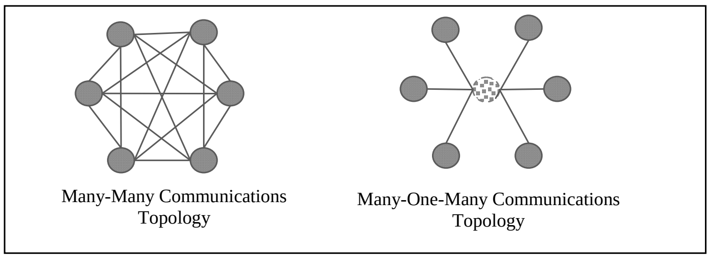


Figure 20. Communications Topology

THIS PAGE INTENTIONALLY LEFT BLANK

III. EXPERIMENTAL DESIGN

A. INTRODUCTION

Simulation models are complex and can contain a huge number of input variables, of which a large number may have significant impact on the MOEs. In addition, many of these input variables are uncertain and their exact values cannot be easily quantified. Furthermore, the response surfaces may be nonlinear (Cioppa, 2002). Hence, it is important that the input variables are sampled across their entire space, while minimizing the amount of design points required to run the simulation experiment. This chapter discusses the variables that are studied, followed by an explanation of the designs used throughout the research. Finally, the processes of running the experiment are discussed.

B. VARIABLES OF INTEREST

In this thesis, the variables that are studied are capability focused. That is to say, only system and equipment characteristics (e.g., probabilities of hit, speed, armor, etc.) are studied. There are two main types of variables in this simulation: controllable and uncontrollable. Controllable factors are referred to as decision factors, those are things decision makers can influence and control. Uncontrollable factors are referred to as noise factors, and include such factors as environmental conditions, enemy capabilities, etc.

In this thesis, the decision and noise factors are taken from two perspectives, one from the perspective of the defender and the other from the attacker. Hence, for the attacker, his decision factors include those of his own systems' capabilities, and noise factors include those of the defender's capabilities and environmental factors, such as population density. Common to both scenarios, the system capabilities factors listed in Table 3 are explored for both the attacker and defender. In addition, the environmental factors of cover and concealment are also explored.

The key difference in the factors explored in the UO and RCO scenario is that in the UO scenario, the additional factor of civilians is explored. In addition, in the UO scenario, the sensor latency factor is not explored for the defender.

S/N	Factor	Remarks
1.	Probability of Hit – Small Arms	System Capabilities
2.	Probability of Hit – Artillery	
3.	Probability of Hit – Antitank Weapons	
4.	Artillery Shot Radius	
5.	Artillery Rate of Fire	
6.	Obstacle Clearance Rates	
7.	Armor – Number of Hits to Kill	
8.	Stealth	
9.	Communications Latency	
10.	Number of Artillery Guns	
11.	Sensor Latency	
12.	Speed	
13.	Terrain – Cover	Environment Factors
14.	Terrain – Concealment	

Table 3. Common Factors Explored for both Attacker and Defender

1. Controllable Factors

This section describes the factors that are being explored and their associated agents.

a. Probabilities of Hit (Small Arms, Artillery, Antitank Weapons)

The probabilities of individual weapon hits are varied to explore the effects of the accuracy of different classes of weapons. For small arms, the weapons that are being explored include those weapons that are being held by the individual soldier and machine guns. These weapons include the M16, AK47, Light Machine Gun (LMG), and General Purpose Machine Gun (GPMG). In terms of antitank weapons, these include the RPGs, Javelin, and 125mm tank guns. For artillery, it is just the artillery guns of the attackers and defenders.

b. Artillery Shot Radius

This factor is intended to help explore the effectiveness and importance of indirect fire weapons with small collateral damage. The damage radius is explored from a range of 1m to 500m.

c. Artillery Rate of Fire

This factor is intended to look into importance of rate of volumes of fire delivered onto a target, i.e., the frequency at which the target is being engaged. In MANA, this is modeled as a probability of engagement per time step. Hence, for a value of 50, this indicates that the chance that a target will be engaged, given that it is identified and classified, is 50%. For values over 100, such as 130, it means that one target will be engaged every time step with a probability of 100%, and a second target may be engaged with a probability of 30%.

d. Obstacle Clearance Rates

This factor explores the rate at which obstacles are being cleared. The values that are being assigned take on a meaning similar to that mentioned in the Artillery Rate of Fire. Every obstacle is assigned a certain number of hits to kill and assigning a clearance rate of 100% would mean that once an obstacle is detected, at every time step, it would be hit once, and once the obstacle's number of hits is reached, it will become cleared. This factor is applied only to the engineer force, which, in the scenario, consists of only the bulldozers and minesweepers.

e. Armor – Number of Hits to Kill

This factor explores the role armor has in operations. It represents the number of hits an armored vehicle can withstand before it is killed. This factor is varied only for the infantry fighting vehicles and tanks. It is varied at a range from 1-10.

f. Stealth

This factor describes the probability of being detected by another agent and is only applied to dismounted troops.

g. Communications and Sensor Latency

This factor explores the importance of timely communications and transmission of information on the battlefield. For this factor, the larger the latency, the

longer it takes for a particular message to be transmitted to the destination unit. In both scenarios, the latency is expressed in seconds; hence, for the experimental design; we are varying the latency to be between 0 (instantaneous) and 900 seconds (15 minutes). For the communications latency, it is applied to all communications links between troops. As for the sensor latency, it is only applied to sensors such as Unmanned Aerial Vehicles (UAVs) and counterbattery radars.

h. Number of Artillery Guns

This is the number of artillery guns that are being deployed on the battlefield and is varied to explore if there is a critical mass of guns that need to deployed before fire support can become effective in determining the battle's outcome.

i. Speed

This is the speed at which vehicles travel on the battlefield and is applied to infantry fighting vehicles and tanks.

2. Noncontrollable Factors

a. Terrain – Cover

This measures the ability of the terrain to provide protection from units firing on it. This is only applied to the buildings and urban area type of terrain for the UO scenario. For the river crossing scenario, it is applied to the buildings, light bushes, and urban terrain.

b. Terrain – Concealment

This measures the ability of the terrain to provide concealment from units firing on it so that they become less detectable. This is only applied to the buildings and also urban area type of terrain for the UO scenario. For the river crossing scenario, it is applied to the buildings, light bushes, and urban terrain.

c. Civilian Density

This factor is explored only in the UO scenario and this factor setting determines the number of civilians in the AO. The purpose of this parameter is to study whether a densely or sparsely populated AO has an impact on the outcome of the battle.

C. EXPERIMENTAL DESIGN AND ANALYSIS PROCESS

Simulation modeling and analysis is done in an iterative manner to ensure that the model functions properly and that the output data is the result of sound assumptions and correct models. An initial exploratory design of a small number of factors is implemented to gain familiarity and understanding of the experimental design process and to identify potential bugs in the model. This is done only with the UO scenario, as the same model components are being reused in the river crossing scenario. Finally, the full experiment where the ranges of the input variables are refined to a tighter bound is run to obtain the final set of results for analysis.

1. Nearly Orthogonal Latin Hypercube (NOLH)

The NOLH was developed by Lieutenant Colonel Thomas Cioppa, United States Army, in 2002. It allows us to efficiently explore simulations with readily available experimental designs. It is a method that considerably improves the space-filling properties of the Latin hypercube, while inducing only small correlations among columns in the design matrix (Cioppa, 2002). The traditional factorial design, with only high and low settings, assumes linearity within the factors and is not able to explore nonlinearities, which are prevalent in simulation models. An NOLH generation tool in Excel, created by Professor Susan Sanchez at Naval Postgraduate School (NPS), is used to generate the NOLH designs for this thesis. The detailed NOLH designs used in this thesis are explained in Appendix B.

2. Exploratory Design

An exploratory design with only 11 factors (33 design points) was carried out using the UO scenario to gain familiarity on experimental design, as well as to gain some initial insights into the model. In this model, only a subset of factors is explored and some

factors are being aggregated (such as probability of hits). A total of nine replications are being carried out for this exploratory design. The factors that are being explored are listed in Table 4, with the scatter plot matrix shown in Figure 21.

S/N	FACTOR	MIN VALUE	MAX VALUE	REMARKS
1.	Weapon Probability of Hit	0.00	1.00	BLUE
2.	Communications Latency	0	900 sec	
3.	Speed	0	72 km/h	
4.	Armor (number of hits)	1	10	
5.	Stealth	0%	100%	
6.	Weapon Probability of Hit	0.00	1.00	RED
7.	Communications Latency	0	900 sec	
8.	Speed	0	72 km/h	
9.	Armor (number of hits)	1	10	
10.	Stealth	0%	100%	
11.	Terrain – Cover	0.00	1.00	Noise Factor

Table 4. Summary of Factors for the Exploratory Design

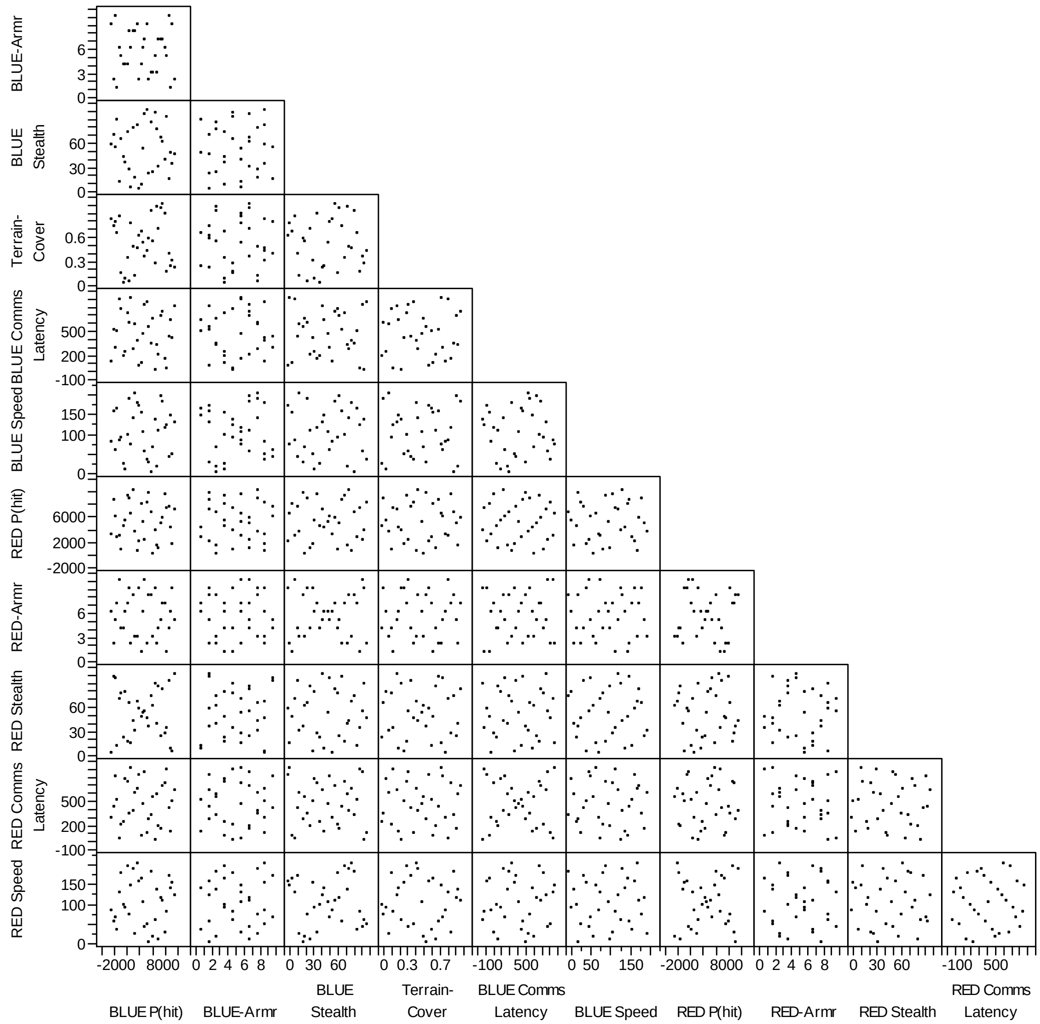


Figure 21. Exploratory Design Scatterplot Matrix

3. Full Design

a. Urban Operations (UO)

Ten replications were made for the UO scenario; with 257 design points for 27 factors, a total of 2,570 runs of the scenario were made. Table 5 shows the summary of all the factors with their maximum and minimum ranges that are explored in the UO scenario. The scatter plot matrix for the full design of the UO model is shown in Figure 22.

S/N	Factor	Min Value	Max Value	Remarks
1.	Probability of Hit – Small Arms	0.01	1.00	ATTACKER
2.	Probability of Hit – Artillery	0.01	1.00	
3.	Probability of Hit – Antitank Weapons	0.01	1.00	
4.	Artillery Shot Radius	1m	500m	
5.	Artillery Rate of Fire	1	200	
6.	Obstacle Clearance Rates	1	100	
7.	Armor – Number of Hits to Kill	1	10	
8.	Stealth	1%	100%	
9.	Communications Latency	0s	900s	
10.	Number of Artillery Guns	1	12	
11.	Reserves Time of Activation	0	1800s	
12.	Sensor Latency	0s	900s	
13.	Speed	1	200	
14.	Probability of Hit – Small Arms	0.01	1.00	DEFENDER
15.	Probability of Hit – Artillery	0.01	1.00	
16.	Probability of Hit – Antitank weapons	0.01	1.00	
17.	Artillery Shot Radius	1m	500m	
18.	Artillery Rate of Fire	1	200	
19.	Stealth	1%	100%	
20.	Armor	1	10	
21.	Communications Latency	0s	900s	
22.	Reserves Time of Activation	0	1800s	
23.	Speed	1	200	
24.	Number of Artillery Guns	1	6	
25.	Terrain – Cover	0.01	1.00	Environment
26.	Terrain – Concealment	0.01	1.00	
27.	Civilian Density	0	600	

Table 5. Factors Used in the Experimental Design for Urban Operations Scenario

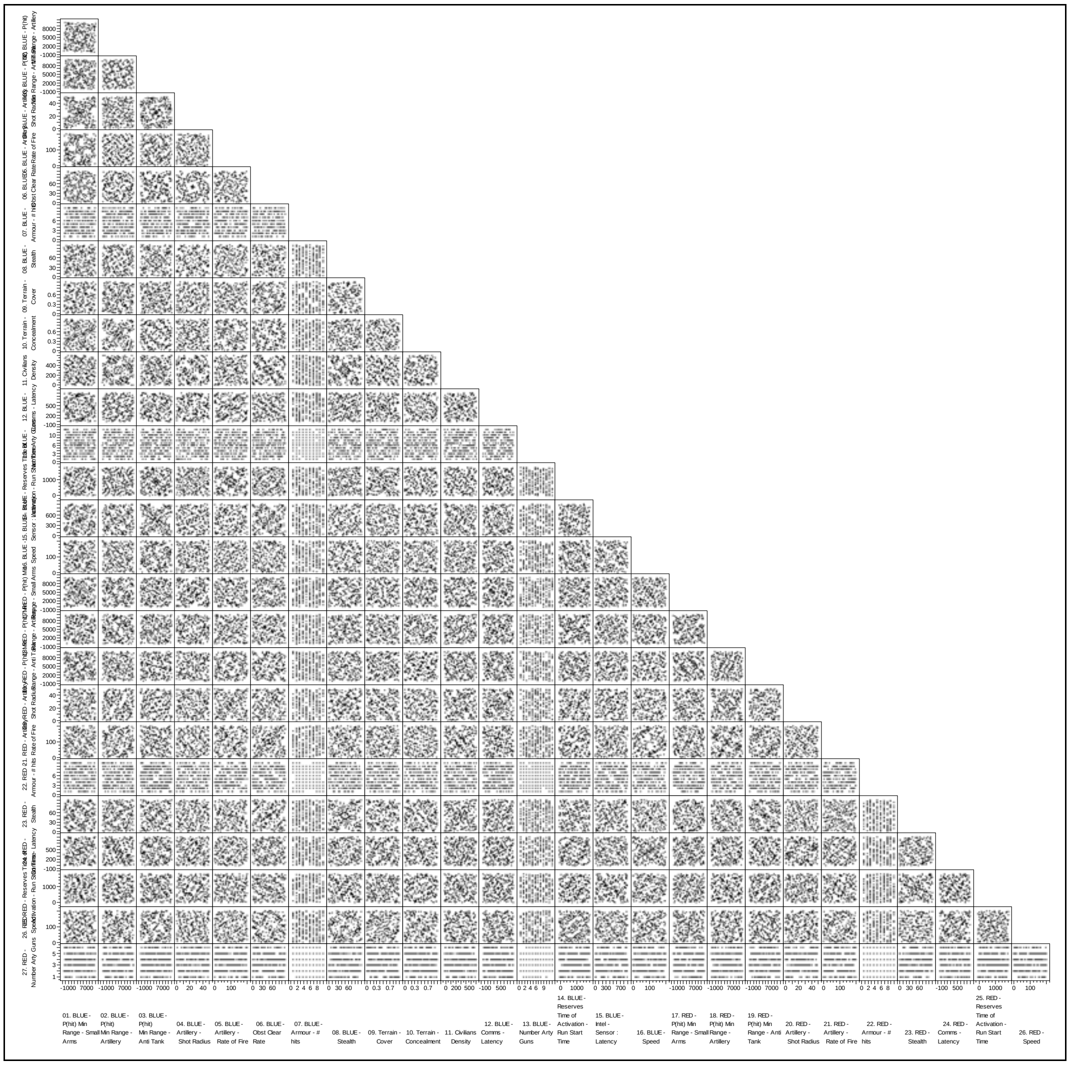


Figure 22. Scatterplot Matrix for the UO Model

b. River Crossing Operation (RCO)

Three replications were made for the RCO scenario, with 257 design points for 27 factors, for a total of 771 runs of the scenario. The extremely small number of replications chosen was a result of the large size of the model taking an extremely long time to complete one single run. From the initial runs, it is estimated that it takes approximately 24 hours to complete a single run of the scenario. Since the scenario is the equivalent of a 12-hour battle in actual operational situations, the ratio of CPU run time to real-world time is 0.5:1.

Hence, for a single replication, it requires 6,168 hours of CPU run time to complete, taking one week to finish on the DSO high-performance computing cluster.

As it is desired to have a higher resolution on the factors influencing the battle outcome in an RCO, the larger design (257 design points) was chosen instead of a smaller one (33 design points). The choice was taken with the understanding that only very strong effects will be identified from the output analysis and trade-offs will have to be made on statistical power. Further studies and more runs, based upon the larger design, can be made in subsequent studies after the completion of this thesis. Table 6 shows the summary of all the factors and their minimum and maximum values.

Table 6. Factors used in the experimental design for the RCO Scenario

S/N	Factor	Min Value	Max Value	Remarks
1.	Probability of Hit – Small Arms	0.01	1.00	ATTACKER
2.	Probability of Hit – Artillery	0.01	1.00	
3.	Probability of Hit – Antitank Weapons	0.01	1.00	
4.	Artillery Shot Radius	1m	500m	
5.	Artillery Rate of Fire	1	200	
6.	Obstacle Clearance Rates	1	100	
7.	Armor – Number of Hits to Kill	1	10	
8.	Stealth	1%	100%	
9.	Communications Latency	0s	900s	
10.	Number of Artillery Guns	1	12	
11.	Sensor Latency	0s	900s	
12.	Speed	1	200	
13.	Probability of Hit – Small Arms	0.01	1.00	DEFENDER
14.	Probability of Hit – Artillery	0.01	1.00	
15.	Probability of Hit – Antitank weapons	0.01	1.00	
16.	Artillery Shot Radius	1m	500m	
17.	Artillery Rate of Fire	1	200	
18.	Stealth	1%	100%	
19.	Armor	1	10	
20.	Communications Latency	0s	900s	
21.	Reserves Time of Activation	0	1800s	
22.	Speed	1	200	
23.	Number of Artillery Guns	1	6	
24.	Sensor Latency	0s	900s	
25.	Terrain – Cover	0.01	1.00	Environment
26.	Terrain – Concealment	0.01	1.00	

D. AUTOMATED RED TEAMING (ART)

Red Teaming is a commonly used technique in military operations to uncover system vulnerabilities and discover weaknesses in military operational concepts. It is a manual process that involves subject matter experts coming together to analyze a given scenario and coming up with situations that are most threatening to BLUE forces. This is often tedious and is limited to the knowledge of the subject matter experts. ART is a framework that was developed by the DSO, Singapore. It employs evolutionary algorithms to discover system vulnerabilities and weaknesses in military operational concepts by automatically using parallel computing techniques. The main purpose of it is to reduce surprise, improve and ensure the robustness of Blue's operational concepts (Choo, Chua, & Tay, 2007), and complement the strengths of the traditional Manual Red Teaming technique.

1. Explore Tactics, Techniques, and Procedures (TTPs)

The purpose of using ART in this scenario is to explore the TTPs of defending forces in urban areas. Typically, in any defense layout, there will be two types of forces: static and dynamic. Static forces are the forces that are deployed to hold and cover grounds of tactical importance (GTI). These are the forces that are the positional elements that provide the frame of a defense layout. Dynamic forces are those that are held in reserve and not committed. Therefore, they can be employed to carry out a wide variety of tasks and are most often used to seize initiative from the attacking force when the situation presents itself. The typical defense layout, shown in Figure 23 is extracted from FM3-90.

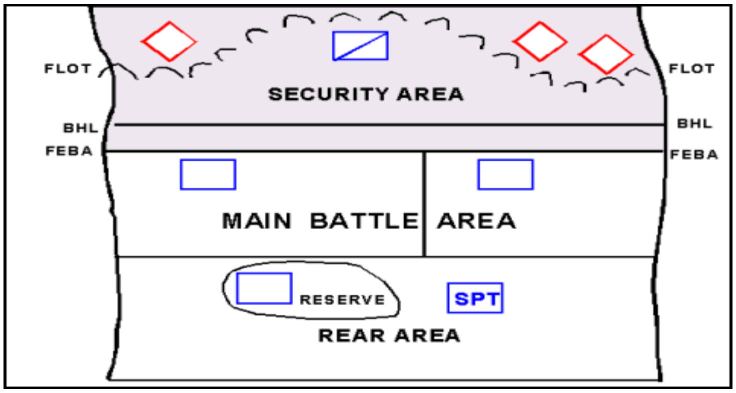


Figure 23. Defense Layout (From Headquarters, Department of the Army, 2001)

The focus of using ART is to explore positions where RED static forces will be deployed and reinforcement routes that will be the most threatening to the attacking BLUE forces.

2. ART Experimental Design

Given the BLUE plan of advancing along two axes and the location of the RED static forces, the reinforcement routes of the RED reserve forces is being explored here. Table 7 shows the factors that are being explored.

Table 7. ART Experimental Design Factors

S/N	FACTOR	MIN VALUE	MAX VALUE	REMARKS
1.	Static Force X coordinates	0.00	1.00	This is applied for each of the 18 agents in the RPG platoon, which forms the static force. This is to say there will be 36 factors (18 X-factors, 18 Y-factors).
2.	Static Force Y coordinates	0.00	1.00	
3.	Reserve Force i^{th} Route X-coordinate *(where i=1,…,12)*	0.00	1.00	For the reinforcement routes, there are 12 waypoints altogether. This makes up a total of 24 factors (12 X-factors, 12 Y-factors). Within each of these factors, the waypoints of the reserve forces are lockstepped together.
4.	Reserve Force i^{th} Route Y-coordinate *(where i=1,…,12)*	0.00	1.00	

E. RUNNING THE EXPERIMENT

MANA uses XML for storage of information relating to the model scenario. With the information stored in XML format, MANA can be readily data-farmable on supercomputer clusters. Running the experiment is a two-step process, which first involves setting a special study file that specifies which entities within the model have specific characteristics (e.g., probability of hit) that are varied. Also, similar to MANA, the ART study file is also specified in XML format to facilitate data farming on clusters. Secondly, with the respective study files, they are sent to the cluster to carry out runs.

1. Creating the Study File

a. NOLH Experimental Design

The tool XStudy, which was created by Steve Upton, Research Associate within the NPS Simulation Experiments and Efficient Designs (SEED) centre, is a very useful tool in assisting users to create their study files. It can be downloaded at *http://harvest.nps.edu/* under software downloads, data farming tools. It is complete with a user guide and is a user-friendly tool using drag and drop functionality. At the end of the process, XStudy automatically generates a zip file that contains all the files required for the run and can be sent to the cluster manager for runs. Figure 24 shows a screenshot of the XStudy tool.

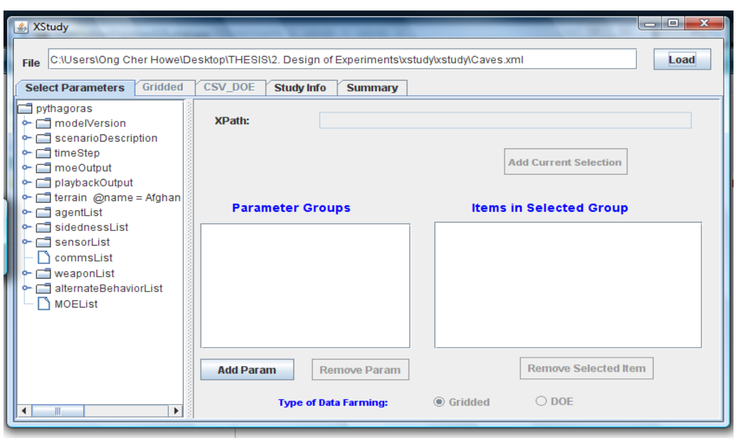


Figure 24. Screenshot of XStudy 1.0

This tool is good for small models, where the parameters to be studied can be selected in a couple of mouse clicks. In large models, involving hundreds of squads whose characteristics must be varied simultaneously (also called lockstepping), additional tools are required to augment XStudy.

As part of the RSG tool in an Excel spreadsheet, a separate design of experiments functionality was also added so that study files can also be rapidly created. It involves first using XStudy to create a sample study file. With that sample file, all the parameters inside are manually deleted through the use of notepad or any text editor. Subsequently, the factors, squads, and paths to be varied are specified in the spreadsheet, and with a click the study file is generated.

b. ART Experimental Design

The ART tool developed by DSO has a graphical user interface that allows users to specify the factors to be optimized and also provides the architecture for runs to be carried out on a single computer. Figure 25 shows a screenshot of the ART graphical user interface.

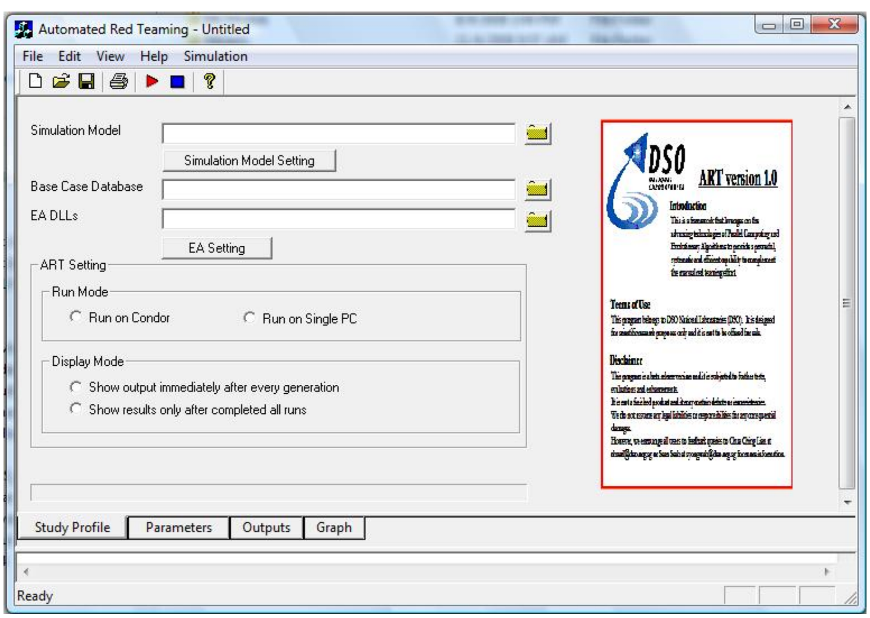


Figure 25. Screenshot of the Automated Red Teaming Tool

2. Running on Cluster of High-Performance Computers

The study file, MANA scenario file, NOLH file, and terrain maps are sent to the cluster manager for runs. In this thesis, two computing clusters were employed in assisting the generation of results. The first one is the NPS SEED cluster managed by Steve Upton and Mary McDonald, and the other is the computing cluster managed by Dave Ang and Chua Ching Lian, DSO, Singapore. The cluster of high-performance computers conducted the simulation in both the exploratory and full designs. The UO full design took about one week to generate 10 replications of 257 design points, which is 2,570 runs of the scenario. The RCO full designs took about one week to generate just one replication of 257 design points.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. DATA ANALYSIS

This chapter describes the process of collating and the processing of the data generated from the runs for analysis. Insights that are gained from the analysis are also discussed.

A. DATA COLLECTION AND PROCESSING

The output file from MANA comes in the format of comma separated values (CSV) files. The summary output files consist of information on the casualties for each of the RED and BLUE forces, as well as the state (dead or alive) of individual squads. Each design point comes with a summary output file that shows the output of the respective replications. In order to process the data from the large number of output files (257), a program was written using VBA to collate the output into one summary output file that could be read into statistical packages for analysis. This summary output file contains information on the design points, as well as the resulting output of the various replications of the individual design points. Analysis was done using JMP 7.0, a statistical package.

B. CLUSTER AND OUTLIER ANALYSIS FOR DATA MINING (COADM)

The statistical analysis is supplemented with a visualization tool developed by the DSO National Laboratories in Singapore. The purpose of COADM is to provide an additional dimension to analysis of the output data. This analysis allows the analyst a quick overview of the “good” and “bad” clusters within the data and identifies the parameters that are associated with the respective clusters. In addition, COADM identifies the outliers in each of the clusters and attempts to discover “surprises” (Choo, Ng, & Chua, 2008)

C. INSIGHTS INTO RESEARCH QUESTIONS

In Chapter I, there are two main questions that need to be answered. These two questions are being addressed through the analysis of the output data, with insights that are gained. To recap, the two research questions are:

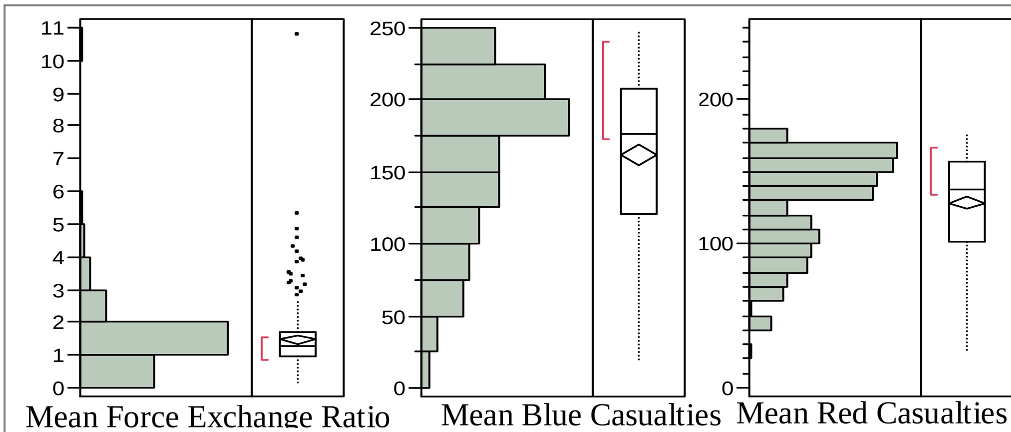
- How effective are communications, sensors, weapons, and platforms with regard to enabling the combat system of systems to complete its mission under the two types of scenarios?
- How do the characteristics of the various terrain (such as urban, rivers) impact the performance of the combat forces?

The questions will be addressed from the perspective of both the attacker and the defender. Several tools are employed to assist in answering these two questions. These include the use of regression analysis, as well as regression trees. Regression tress provide a simple and intuitive summary to models containing a large number of variables.

1. Urban Operations (UO) – Effects of System Capabilities

a. Distribution of Red and Blue Casualties, Force Exchange Ratio

Figure 26 shows the distribution of RED and BLUE casualties and the Force Exchange Ratios.



Mean Force Exchange Ratio	
Mean	1.4685575
Std Dev	1.0095665
Std Err Mean	0.0635967
Upper 95% Mean	1.5938087
Lower 95% Mean	1.3433063
N	252

Mean Blue Casualties	
Mean	162.06825
Std Dev	56.639586
Std Err Mean	3.5679585
Upper 95% Mean	169.09521
Lower 95% Mean	155.0413
N	252

Mean Red Casualties	
Mean	128.17857
Std Dev	33.932563
Std Err Mean	2.1375505
Upper 95% Mean	132.38839
Lower 95% Mean	123.96875
N	252

Figure 26. Distribution of Red and Blue Casualties, and Force Exchange Ratio

From Figure 26, we see that overall, across a spectrum of system capabilities (both red and blue forces) and terrain conditions (civilians, cover and concealment), the attacker (Blue) suffers more casualties than the defender (Red). The average force exchange ratio is around 1.5 Blue forces for every Red force attrited (1.469 from Figure 26), or more simply, for every two Red units attrited, three Blue forces are attrited. We can see that, on average, the urban battlefield is one that is disadvantageous to the attacker.

In addition, we see that the variability in casualties suffered by the Blue forces is also 70% higher (standard deviation of 56 for Blue versus 33 for Red) than that of the Red forces. A plot of red casualties against blue casualties is shown in Figure 27.

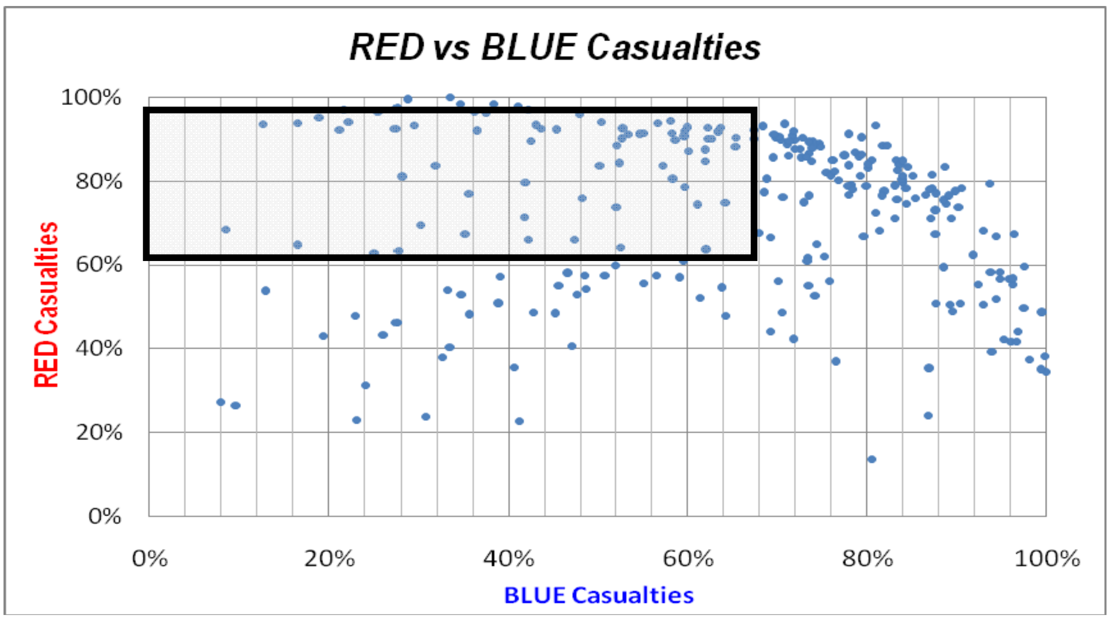


Figure 27. UO Scenario – Plot of Red Casualties against Blue Casualties

From Figure 27 we can see that for mission success, which is defined as inflicting at least 67% Red casualties and losing less than 67% of Blue forces, over a wide spectrum of capabilities and terrain conditions, only about 92 design points out of the 252 are mission successes for the attacker. This translates to an approximately 26% chance of mission success in a UO scenario.

b. Factors Influencing Extent of Red Casualties

Figure 28 shows the regression tree analysis on factors influencing the defender casualties.

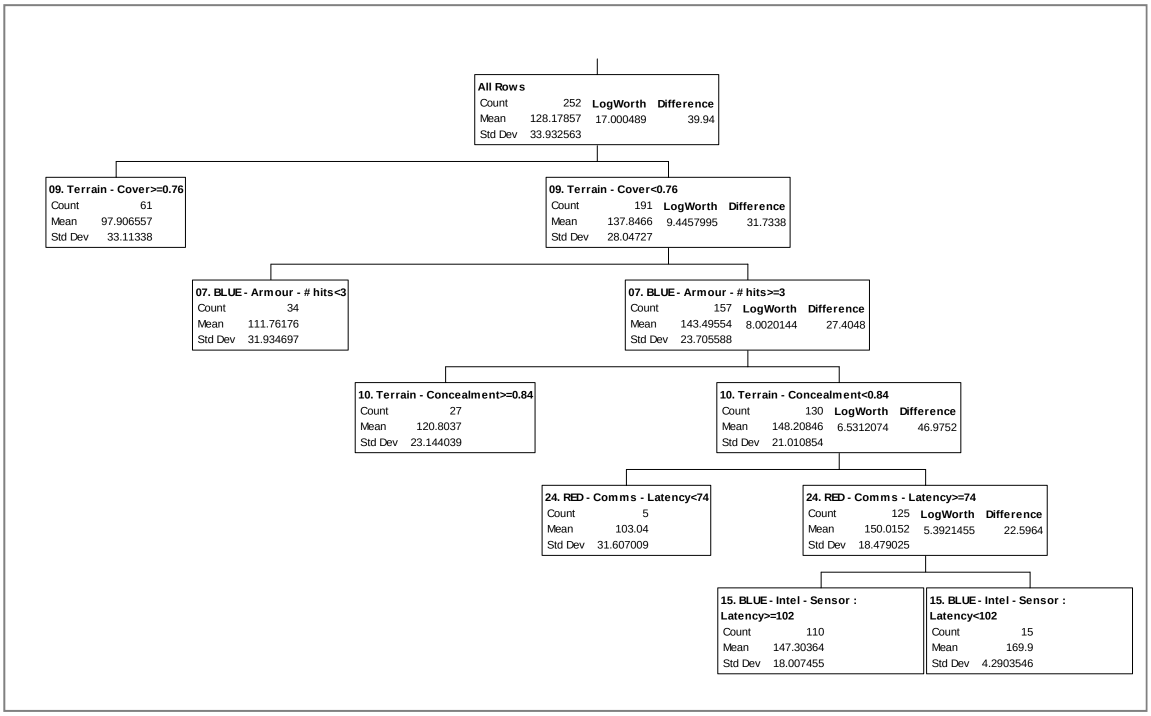


Figure 28. Regression Tree Analysis on Factors Influencing the Defender Casualties

From Figure 28, we can see that cover provided by the terrain has the most impact in terms of influencing the extent of red casualties. Without sufficient cover from the surrounding terrain, in this case the buildings within the urban terrain, the next factor that then becomes important is Blue’s armor protection capability. This is measured by the number of hits the armored vehicle can sustain before being attrited. From the regression tree, this number is three.

This is a particularly interesting observation, as we can see that in an urban combat scenario, it is important to have good survivability before you are able to successfully inflict casualties on the enemy. The lethality of weapons is secondary to that of survivability. From observing a couple of the simulation runs of the UO scenario, it

can be seen that it is important to be able to provide sufficient armor protection to the attacking forces in the advance to the objective to fight the defending red forces.

For defending forces, it means that better armor-defeating capabilities (better antitank weapons) would be the key to reducing their own casualties.

In addition, the exploitation of terrain in providing cover and concealment will contribute to lower casualties as well.

c. Factors Influencing Extent of Blue Casualties

Figure 29 shows the regression tree analysis on factors influencing the attacker's casualties.

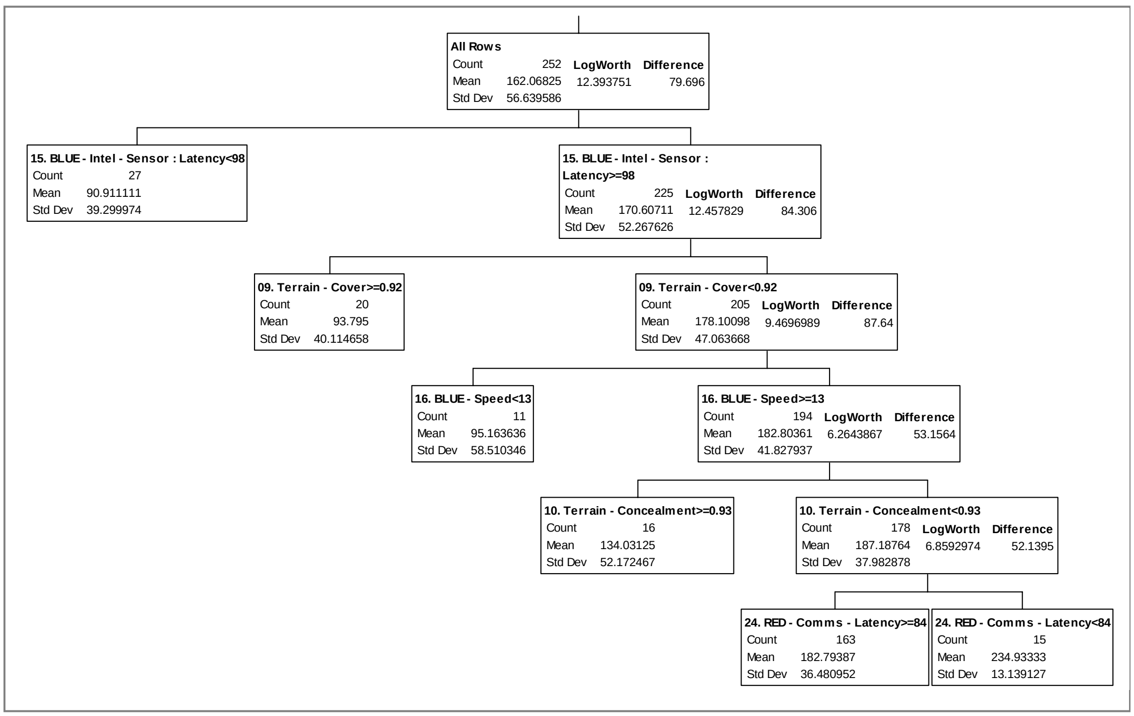


Figure 29. Regression Tree Analysis on Factors Influencing the Attacker Casualties

As for the casualties suffered by the attacking Blue forces, the first critical factor is, in fact, sensor latency. The sensors that this factor specifically refers to are the UAV, as well as the counterbattery radar that the battery supporting the attacking mechanized infantry battalion is equipped with. From Figure 29, we can see that a latency

in delivering information from the sensor to the shooter of more than 1.5 minutes (98 seconds) almost doubles the mean casualties (from around 90 to 170) suffered by the Blue forces. This demonstrates the importance of not just accurate information, but also information that is timely.

A rerun of a couple of simulation runs indicates that when information is delivered with a long delay, it often becomes obsolete and subsequent actions, such as calling for artillery fire, will result in attacks on a nonexistent target. This is especially critical when targeting mobile reserves, where the target window of opportunity opens and closes very rapidly. In observing the simulation runs, it is seen that if the targeting effort on the defenders' reserves is not executed well, it could result in the attacking forces having to deal with the reserves that leaked from the targeting effort, thus increasing casualties in the ensuing combat at the frontal positions. This is especially so for armored forces, where they move very fast.

From the output, we also note that if the latency in the attacker's sensor-shooter chain is more than approximately 1-2 minutes, the attacker must move slower to avoid casualties. The number of casualties sustained by the attacker is halved (from 183 – 95) if the attacker moves slower. The results indicate that the movement speed should be slowed to around 1 m/s (13 grids in 10 seconds) or about 4km/hr, which is approximately the marching speed of infantry troops. A review of the simulation runs indicate that given a higher latency, there is a need to allow time for the artillery fires to soften the defender positions before the troops move in to secure the objective.

In addition, with higher sensor-shooter latency, the defender's mobile reserves could not be easily targeted en route to the forward positions. A slower speed would trigger the defender's reserves to the forward positions first and without the attacker engaging in decisive combat with the deployed reserves. The defender's deployed reserves would then be exposed to artillery fires from the attacker. This will make it easier for the attacker to capture the objectives once they arrive, albeit at a slower speed.

From the regression tree analysis, it appears that for the defending Red forces, the most important factor to increasing Blue casualties is responsive communications. What this means for the attacking Blue forces is that by jamming communications of the Red forces prior to attacking, it is expected that a lower casualty rate can be achieved.

d. Factors Influencing Extent of Force Exchange Ratio

Figure 26 shows the distribution of RED and BLUE casualties and the Force Exchange Ratios.

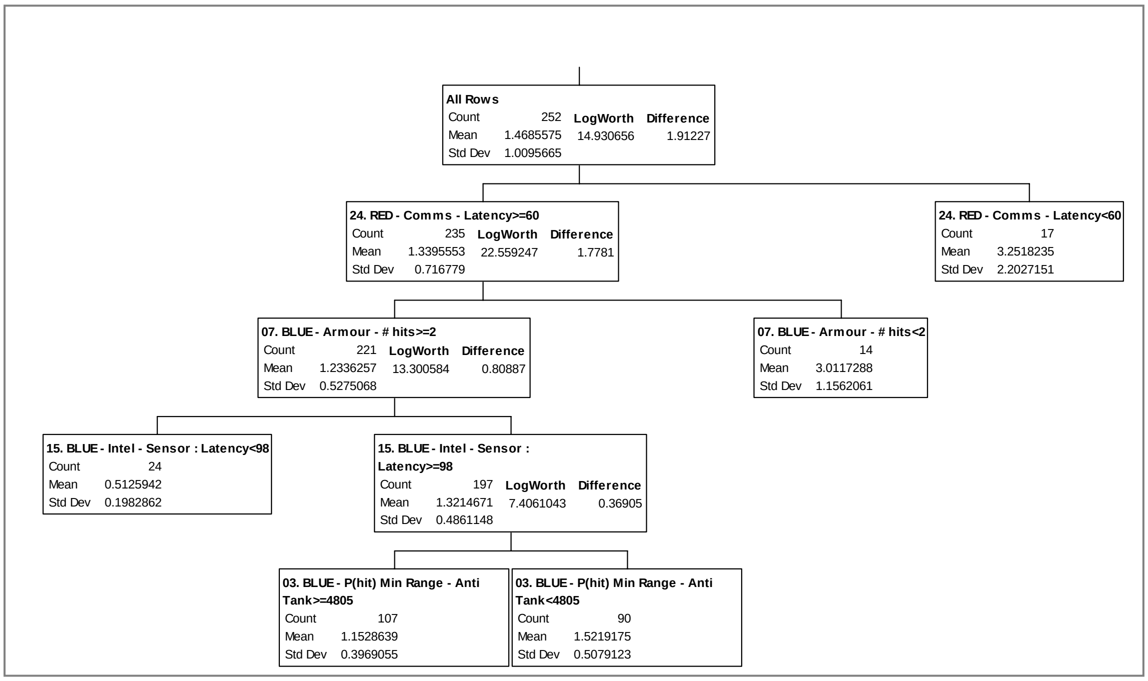


Figure 30. Regression Tree Analysis on Factors Influencing the Force Exchange Ratio

We can see from Figure 30 that given terrain is neutral, that is it does not feature itself within the regression tree analysis. The factors that were analyzed in Blue and Red casualties also are dominant factors influencing the force exchange ratio as well. In addition, we can see that weapon lethality of antitank weapons is the additional factor that comes into effect for force exchange ratios.

The regression tree analysis revealed that when the armor of the attacker is able to sustain at least two or more antitank hits, the force exchange ratio turns dramatically in favour of the attacker, from 3.0 to 1.2, a more than 50% improvement. Incidentally, the result also reveals that when armor protection is insufficient for the attacker (less than two hits), the traditional 3:1 ratio of attacker-defender applies in this UO scenario.

e. Factors That Can Influence Variability in Battle Outcome

Figure 31 shows the regression tree analysis on factors influencing the variability in force exchange ratio.

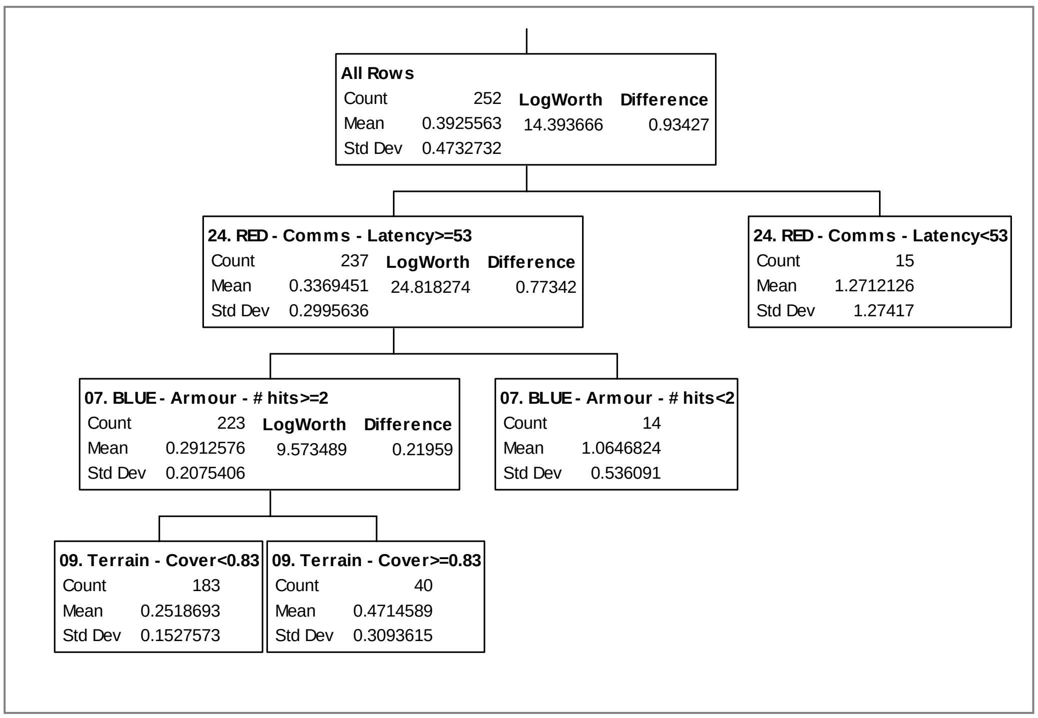


Figure 31. Regression Tree Analysis on Factors Influencing the Variability in the Force Exchange Ratio

We want to identify capabilities that will minimize the variability in battle outcomes. This is done by considering the standard deviations of the force exchange ratio against all the input parameters. From Figure 31, we can see that the two main factors are communications responsiveness of the defending Red forces and the armor of the

attacking Blue forces. These are also the two factors that have effect on the mean of the force exchange ratio as well. Hence, the robust strategy for the attacking Blue force would be to focus on better armor protection and employing jamming techniques to degrade the communications of the defending Red force. Conversely, for the defending Red force, it would be to explore the use of better anti-armor weapons, deploy effective communications links, and ensure that the communications links are not susceptible to jamming by the attacker.

f. Cluster and Outlier Analysis

Figure 32 shows an overview of the factor settings in the Design of Experiments, as well as the distribution of the MOE output over all the design points.

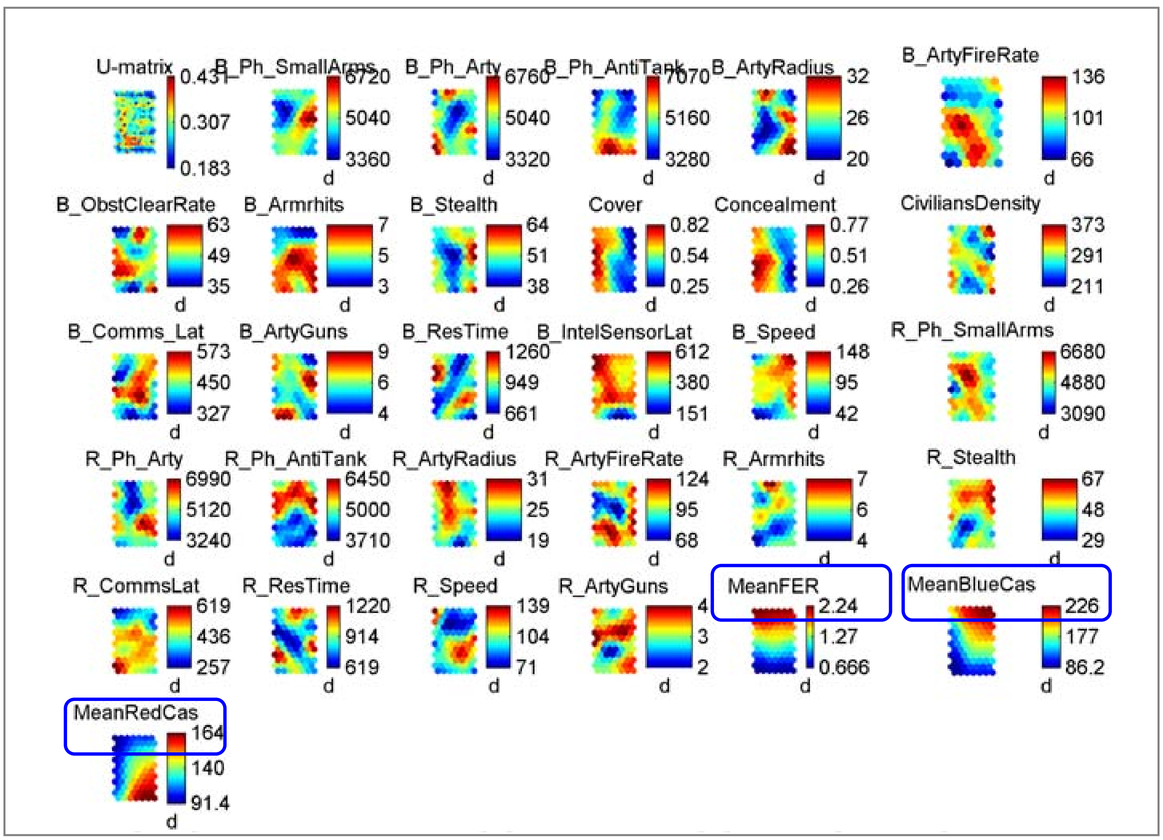


Figure 32. Overview of Correlation Plots for Urban Operations

The MOEs that are studied in this COADM analysis are the Mean Force Exchange Ratio, and Mean Red and Blue Casualties. The rectangle that goes from Blue to Red on the right side of the colored patterns represents the factor settings. Blue represents low and Red represents high. The colored patterns represent how the high and low settings are distributed. The various factors can then be read by comparing against other factor settings or by comparing with the MOE output. For instance, for the three MOEs, we can see that with a high mean Blue Casualty, low mean Red Casualty, the Mean Force Exchange Ratio will be high.

From the correlation plots with different colored patterns, we can see that there is little correlation between the input factors. This is expected, since the NOLH designs ensure almost orthogonality among the input factors. Figure 33 shows the factors that appear to have high correlation with the MOEs, i.e., the colored patterns of the factors vary very closely with changes in the MOEs.

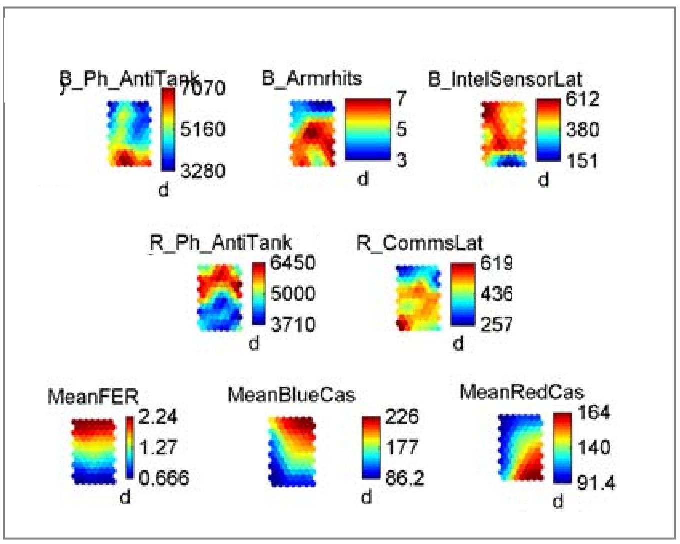


Figure 33. High Correlation between Factors and MOE for Urban Operations

The factors that are identified as important are:

- Blue's antitank weapons probability of hit
- Blue's armor protection
- Blue's sensors' latency in information transmission
- Red's antitank weapons probability of hit
- Red's communications latency

These are factors that were also identified in the regression tree analysis and are consistent with that analysis. Figure 34 shows the outliers that are identified in the respective clusters in the output data.

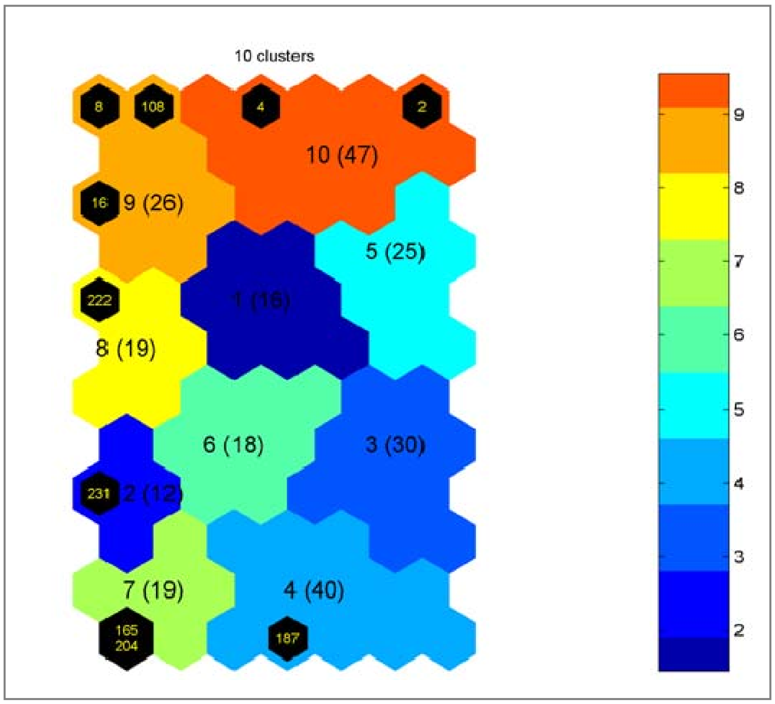


Figure 34. Outlier Identification in Urban Operations Model

Taking into consideration the MOEs and also the input factors, COADM generated a total of 10 clusters. Within these 10 clusters, 10 outliers were identified and are found in clusters 2,4,7,8,9,10. In this outlier analysis, we will classify clusters where

the mean force exchange ratio is less than 1.0 as “clusters.” This means that it takes less blue casualties to exchange for red casualties. Table 8 shows the mean force exchange ratio of the various clusters.

Cluster S/N	Mean Force Exchange Ratio	Mean Red Casualties	Mean Blue Casualties	Outliers
1	0.832	161.400	125.000	Nil
2	1.012	131.500	121.300	231
3	1.531	105.300	174.900	Nil
4	2.120	95.700	197.200	167
5	1.405	143.300	200.700	Nil
6	1.286	140.700	178.700	Nil
7	1.771	117.400	218.700	165, 204
8	0.728	133.900	90.200	222
9	1.120	158.400	175.400	16, 8, 108
10	1.179	101.400	120.900	2, 4

Table 8. COADM Individual Cluster MOE

We can see that in the table, there are only two “good” clusters, which corresponds to clusters 1 and 8. This also agrees with the analysis that in an urban combat scenario, the exchange ratio favors the defender and that the attacker will, more often than not, need to devote more forces for an urban fight.

The next analysis is on looking for “good” outliers in “bad” clusters and also “bad” outliers in “good” clusters. In this analysis, a “good” is defined as having a force exchange ratio that is less than one. This can be interpreted as having an exchange ratio that is in favor of the attacker. This analysis seeks to uncover any possible surprises that may come out as a result of unexpected combinations in the input variables. The detailed output data is shown in Appendix C. From analysis of the individual outlier data, we see that there is only one “bad” outlier in the “good” clusters. It is identified as point 222, with a force exchange ratio of 1.87 in a cluster where the average is 0.728, with a standard deviation of 0.248. A review of the settings show that in point 222, the antitank weapon probability of hit for the attacker is set at 0.0001, which is effectively almost zero.

We see that the since the antitank weapon probability of hit is one of the key factors in influencing the force exchange ratio, it is likely that this setting caused the outlier.

There are three good outliers in two "bad" clusters, they are 165 and 204 in cluster 7 and 231 in cluster 2. For points 165 and 204 (with force exchange ratio of 0.35 and 0.43 with a cluster average of 1.286), it was found that in these two points, the attacker moves at very low speed (the setting is equivalent to approximately half the walking speed of 1m/s) and the sensor latency is approximately 5 minutes. This agrees with the previous analyses that when there is a high sensor latency of more than 1-2 minutes, the attacker should advance at speeds lower than walking speed. This will result in a reduction of the attacker's casualties by 50%. In the case of point 231 in cluster 2 (at 0.93 with a cluster average of 1.012), it is likely that the outlier was caused by a Blue stealth setting of 100%.

g. Red Teaming (Manual and Automated)

In this section, the results from red teaming (defender) are discussed. A manual red teaming was carried out in International Data Farming Workshop 17, held in Garmisch, Germany. The focus of the manual red teaming effort during that study in the workshop was to explore the TTPs of the defender in an urban terrain with the aim to minimize own casualties and maximize the attacker's casualties. Specifically, the aim was to gain insights into how the defender should deploy his static forces and also how he should deploy his reserves. The results show that by uniformly distributing his static forces along the main axes and deploying his reserves from the flanks of the attacker, the defender can tilt the force exchange ratio to his advantage. This strategy is robust as well, since the standard deviation of the force exchange ratio is also the smallest. The detailed report for the workshop is as attached in Appendix D.

ART employing the tool developed by DSO National Laboratories, Singapore was also applied on the UO scenario. However, the runs crashed prematurely as it was not able to handle a large scenario. DSO National Laboratories has taken steps to improve ART for use on larger scenarios.

2. River Crossing Operations (RCO) – Effects of System Capabilities

As a result of computing resource constraints, only a single replicate is obtained for the output for the river crossing scenario. These findings should be considered exploratory, and follow-on studies can continue with more runs to produce findings that are statistically stronger.

a. Distribution of Red and Blue Casualties, Force Exchange Ratio

Figure 35 shows the distribution of RED and BLUE casualties and the Force Exchange Ratio for the river crossing scenario.

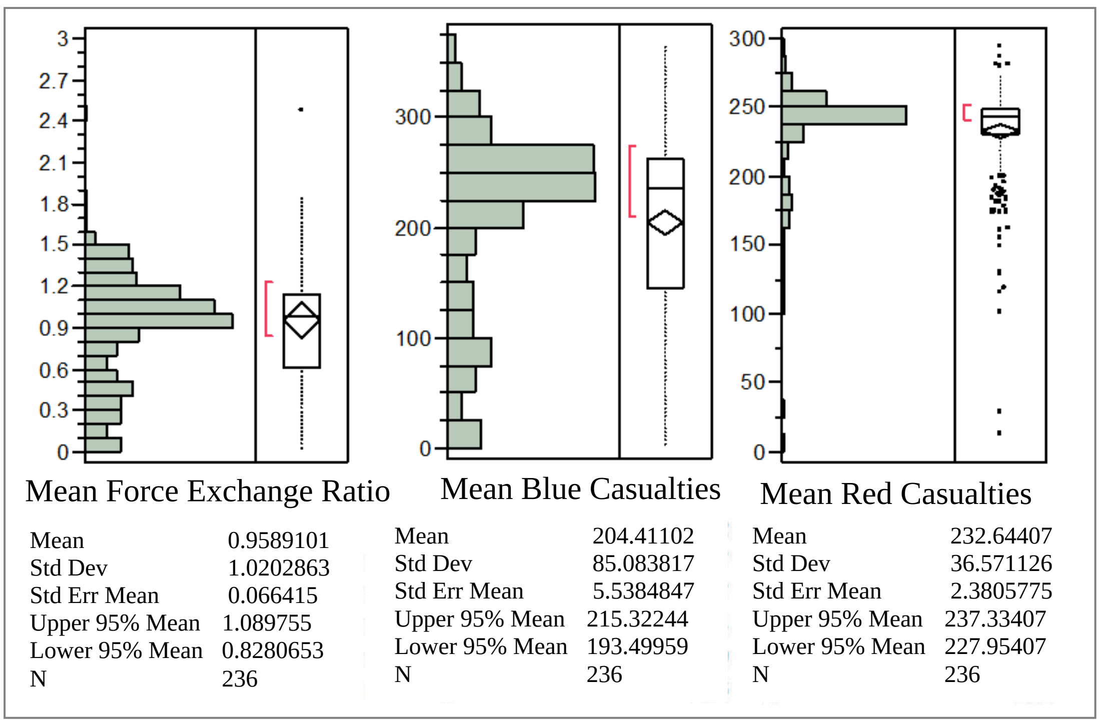


Figure 35. Distribution of RED and BLUE Casualties, and Force Exchange Ratio for RCO

From the distribution plot, we see that in general for an RCO, the mean exchange ratio is around 0.95 (about one attacker to every one defender casualty). Figure 36 shows the plot of RED against BLUE casualties.

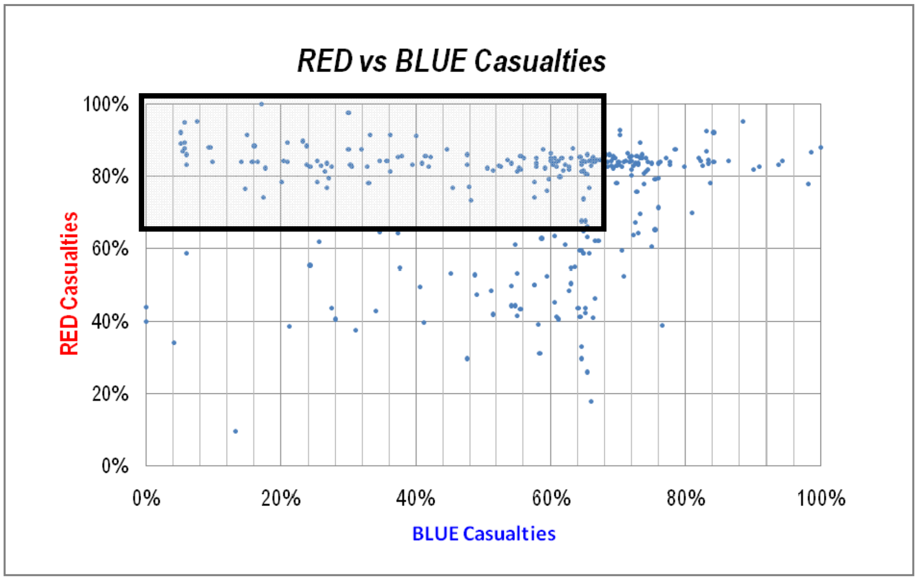


Figure 36. RCO – Plot of Red Casualties against BLUE Casualties

From Figure 36, the green box shows the region where there was a mission success for the attacker. A count reveals that 123 of the 236 runs are mission success for the attacker. This implies that over a wide range of capability settings and terrain conditions, the attacker has a 52% chance of success in an RCO.

When this is compared to the UO scenario, we see that the attacker has twice as many chances for success in an RCO than in UO.

b. Factors Influencing Extent of Red Casualties

Figure 37 shows the regression tree analysis for RED casualties in the river crossing scenario.

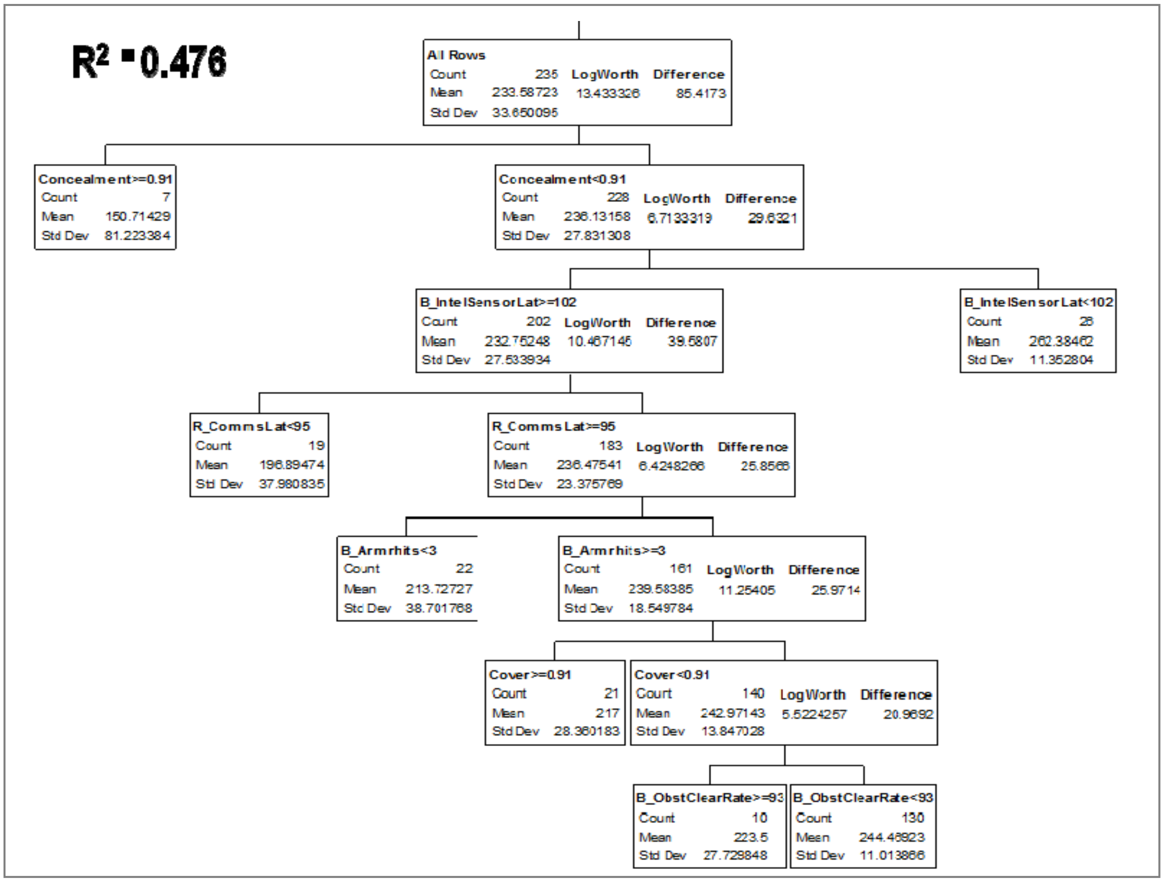


Figure 37. RCO Regression Tree Analysis for RED Casualties

From Figure 37, we can see that terrain concealment is the first most important aspect in determining red casualties. By operating in terrain that has excellent concealment, RED is able to reduce his casualties by more than 30%. Terrain with excellent concealment allows the defender to stay undetected by the attacker's sensors (consisting of both UAVs and artillery counterbattery radar). This reduces casualties, as the defender's forces cannot be easily targeted. The next split corresponds to BLUE's sensor latency, confirming that the attacker's sensors are effective when the terrain concealment is low. What this means for the defender is that in a densely vegetated terrain, he should exploit the overhead foliage to reduce his vulnerability. For the attacker, the implication is that having sensors that can penetrate foliage will greatly enhance his targeting effectiveness and eliminate the defender's advantage within the terrain.

In the case where both BLUE's sensor and RED communications latency is more than 1.5-2 minutes, survivability of both the RED and BLUE forces becomes an important factor in determining the level of red casualties. This is obvious from the subsequent splits of BLUE armor—number of hits and terrain cover. We can see from Figure 37 that the number of antitank hits the attacker's armor can sustain is an important factor in determining the defender's casualties. The threshold of three hits that was identified in the RCO scenario is similar to that found in the UO scenario.

c. Factors Influencing Extent of Blue Casualties

Figure 38 shows the regression tree analysis for BLUE casualties in the river crossing scenario.

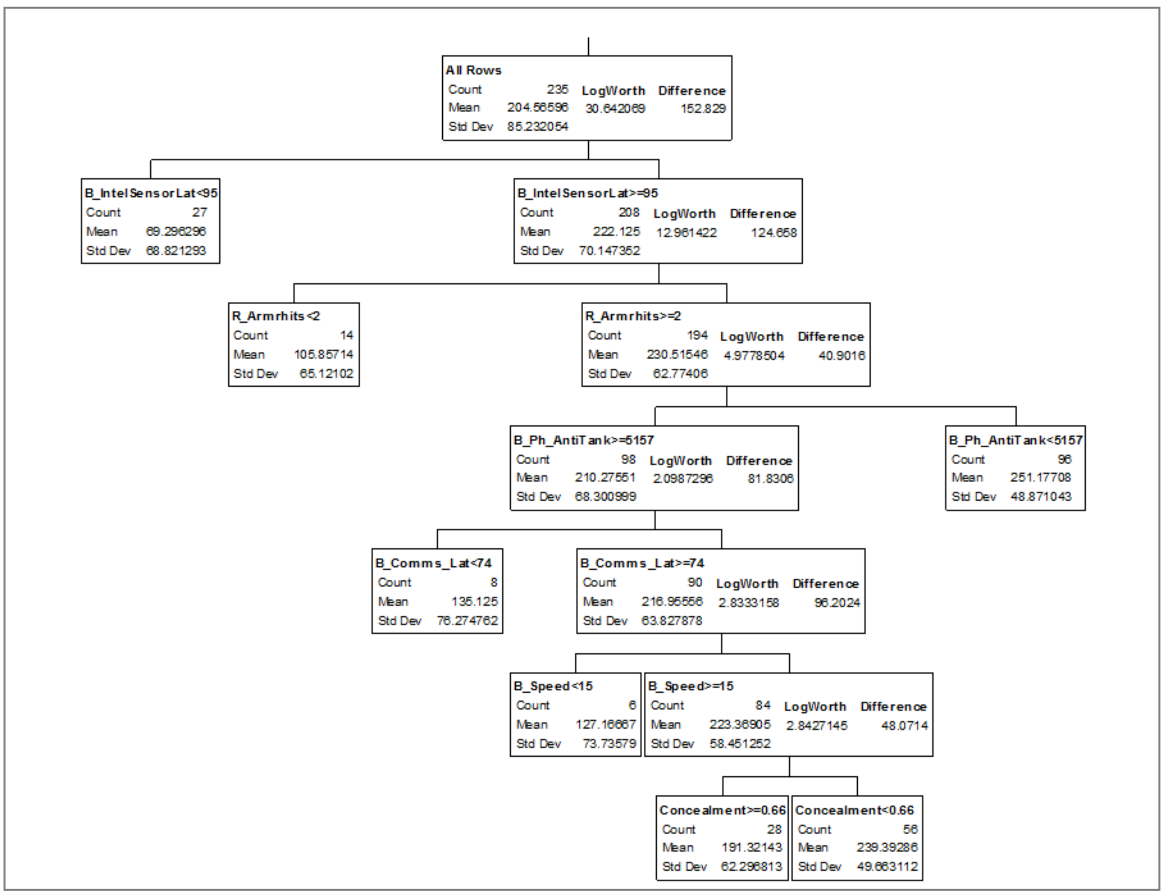


Figure 38. RCO Regression Tree Analysis for Blue Casualties

From Figure 38, we can see that with the attacker having a sensor latency of less than 1.5 minutes will result in a casualty rate that is lower by more than 67% (from 222 to 69). The importance of the sensor is two-fold, one for the targeting of the Red reserves and secondly for the artillery battle (counterbattery fires) in the scenario. A successful counterbattery fire will reduce the exposure of the attacker to artillery fires as he crosses the river and in subsequent advance to the objectives. Effective targeting of the defender's reserves will also deny the defender the opportunity to mass combat power at the crossing sites to defeat the elements of the attacker's forces that have crossed the river.

From the regression tree, we can see that if the targeting effort is not effectively carried out, where a significant portion of the reserves are able to mass at the forward positions, it is the number of hits the defender's armor is able to sustain that will determine the attacker's casualties. In cases where the targeting effort is not effective, closer-range weapons, such as antitank weapons, need to be more effective. This is evident from the split in the regression tree indicating the importance of a higher probability of hit for the antitank weapons of the attacker to reduce own casualties.

Another important observation to note from Figure 38 is that when sensor and communications latency is high (>1-2 min) the attacker should advance at a rate that is almost equivalent to infantry marching speed. This is a finding that agrees with that concluded in the UO scenario.

d. Factors Influencing Force Exchange Ratio

Figure 39 shows the regression tree analysis on the force exchange ratio in the river crossing scenario.

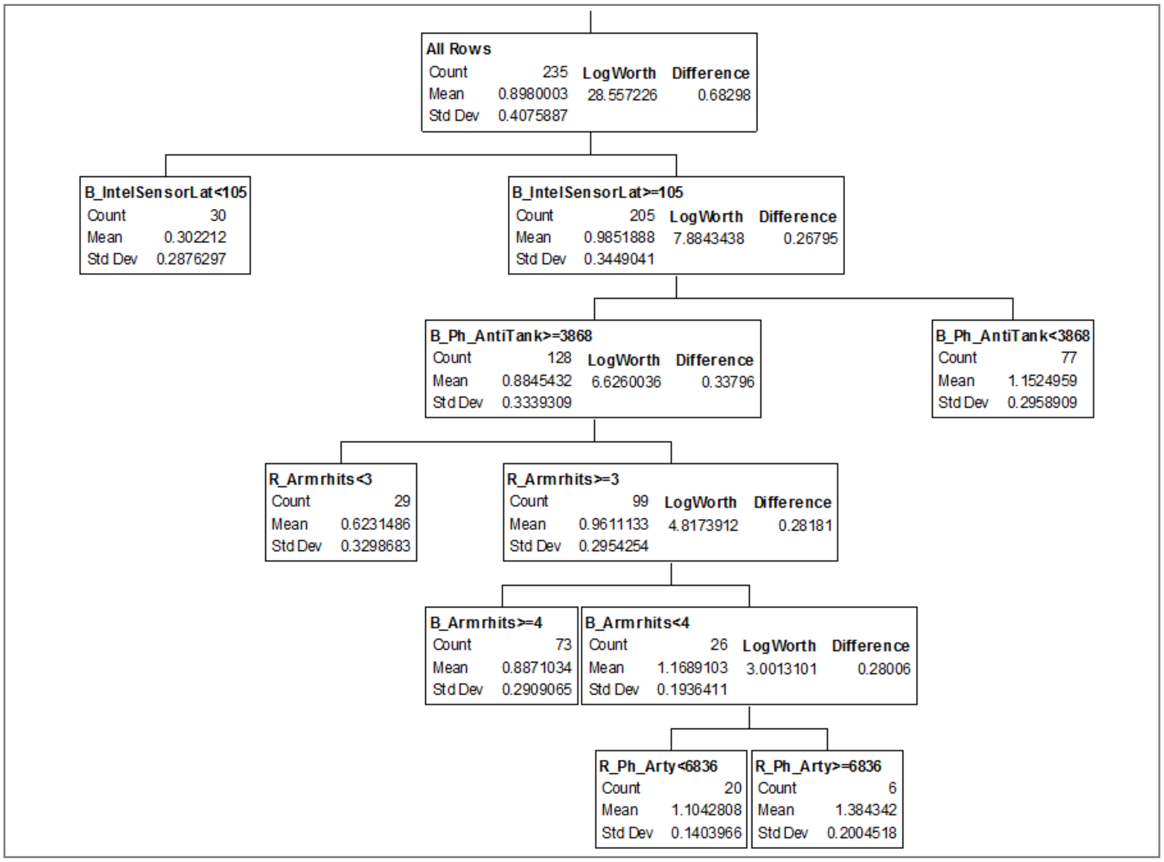


Figure 39. RCO Regression Tree Analysis for Force Exchange Ratio

From Figure 39, we can see that the key determining factor for the force exchange ratio is the attacker's sensor latency. If the latency is less than 1.5 – 2 minutes, the mean exchange ratio is about three RED casualties for every BLUE casualty, which is very favorable for the attacker. If the latency is higher than that, the mean exchange ratio goes up to one red casualty for every BLUE casualty.

From the regression tree, we can also deduce that when targeting is not effective, the attacker will need effective antitank weapons that will be able to take out the defender's reserves that manage to mass at the forward positions. It is at this point where the number of hits the defender's armor is able to sustain makes a difference to the force exchange ratio. From this observation, we can conclude that where possible, the defender should deploy reserves from armored vehicles (able to sustain at least three antiarmor hits) instead of soft-skin vehicles.

e. Cluster and Outlier Analysis

Similar to the UO scenario, a cluster and outlier analysis is carried out as well. The detailed output data is shown in Appendix C. The MOEs are shown in the circled box in Figure 40.

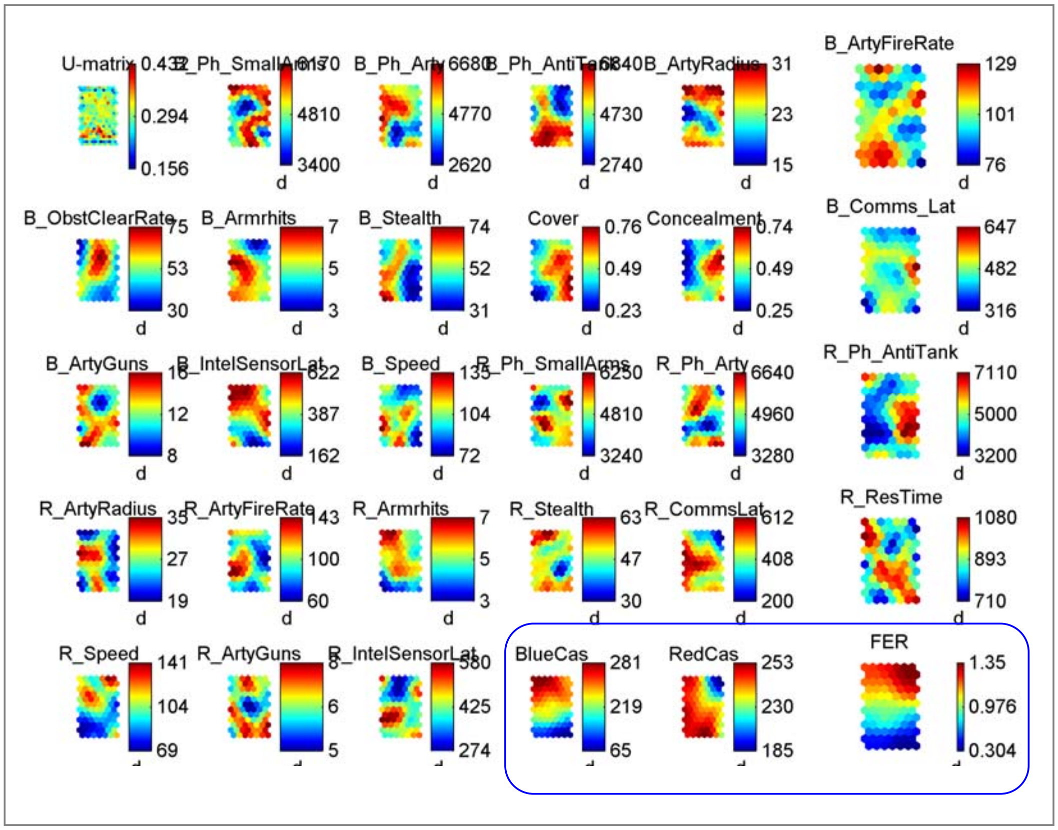


Figure 40. Overview of Correlation Plots for River Crossing Operations

From the correlation plots with different colored patterns, we can see that there is little correlation between the input factors. Again, this is expected as a feature due to the NOLH experimental designs. Figure 41 shows the factors that have high correlation with MOEs.

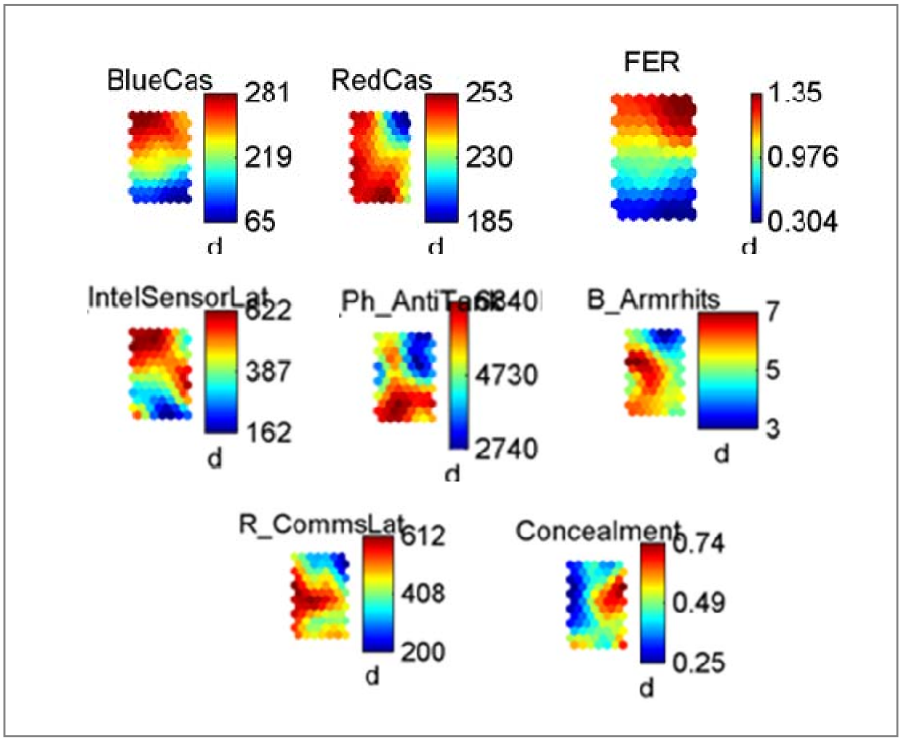


Figure 41. High Correlation between Factors and MOE for River Crossing Operations

The input factors that have relatively higher correlation with the measures of effectiveness are listed as follows:

- Attacker's sensor latency
- Attacker's antitank weapons probability of hit
- Number of hits the attacker's armor can sustain
- Defender's communications latency
- Terrain concealment

This agrees with the findings from the regression tree analysis that was done prior to the cluster and outlier analysis.

Figure 42 shows the identification of outliers in the output data for the river crossing scenario.

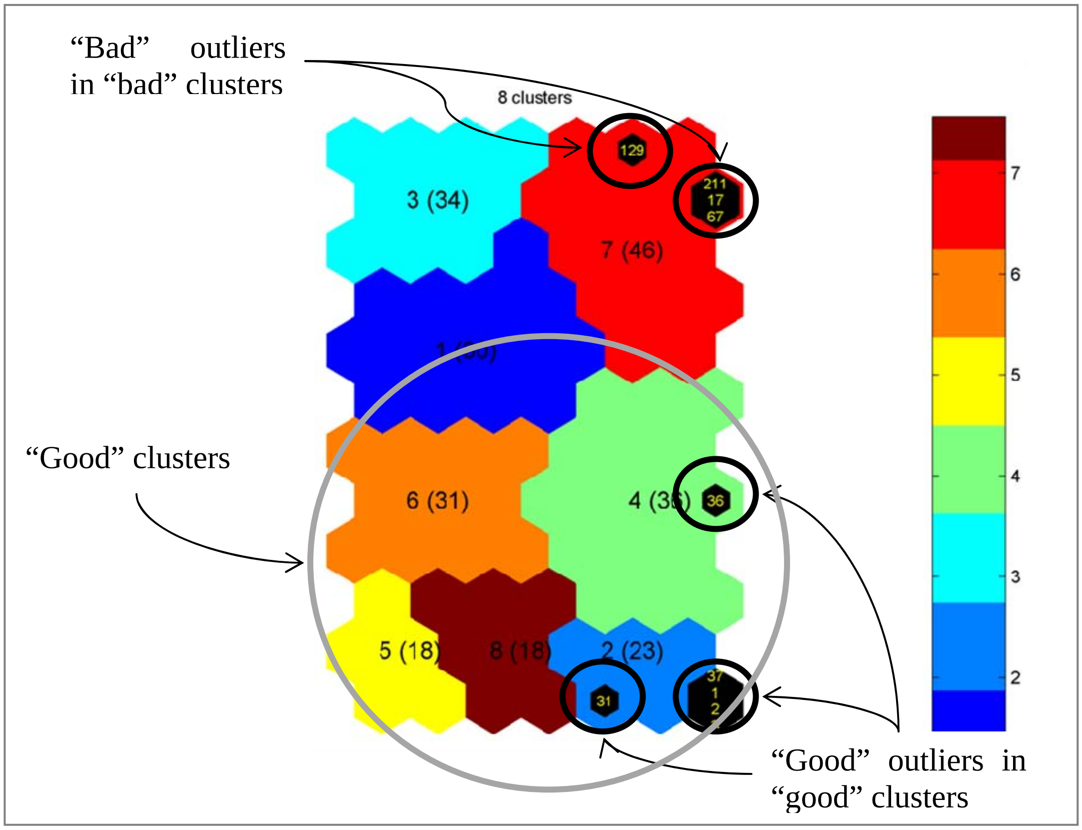


Figure 42. Outlier Identification in River Crossing Operations Model

From the output from the outlier analysis, clusters 2, 4, 5, 6, 8 are identified as "good" clusters. These are clusters having a force exchange ratio of less than 1.0. In addition, the outliers that are identified within the output data are either in the case of "bad" outliers in "bad" clusters or "good" outliers in "good" clusters. To put it simply, in clusters with a mean force exchange ratio of lower than 1.0 ("good"), all the outliers have force exchange ratios of lower than that of the cluster mean.

In addition, in clusters with a mean force exchange ratio of higher than one ("bad"), all the outliers have force exchange ratios that are higher than the cluster mean. There are no "surprises" that we need to explore in the output data.

V. CONCLUSIONS AND RECOMMENDATIONS

A. RESEARCH SUMMARY

Every system and weapon will have to operate with other weapons or systems to fight as a single entity during combat. This research sets out to propose a capability-focused framework, using a synthesis of different computer simulation techniques to analyze a system of systems, in order to better understand how they perform under various stressful operational environments. Using the river crossing and UO as the background for the scenarios, this thesis generated detailed analysis on the influence of the various types of capabilities on battle outcomes. The simulation work from this thesis provided the framework and also tools for the future use of ABMs in analyzing large-scale combat systems.

B. RESEARCH QUESTIONS

The goal of this thesis was to provide insights into the following questions:

- How effective are communications, sensors, weapons, and platforms with regard to enabling the combat system of systems to complete its mission under the two types of scenarios?
- How do the characteristics of the various terrain (such as urban areas, rivers) impact the performance of the combat forces?

This chapter briefly summarizes the insights and answers into these questions.

1. Effectiveness of Communications, Sensors, Weapons, and Platforms

From the analysis, it revealed that there are two recurring observations in both scenarios. In the case for the attacker, the armor protection should be capable of sustaining at least three antitank hits. This produces higher casualties for the defender. The second recurring observation is that for targeting of the reserves to be effective, the latency of the sensors (e.g., UAV and counterbattery radar) in transmitting information back to the shooter (artillery units) will have to be less than approximately 1.5 to 2 minutes.

If the sensor-shooter latency is more than that threshold, then it becomes important for the closer-range antitank weapons to be effective to take out the defender's reserves.

For the defender, it is observed that in both scenarios, communications latency is the main factor that is within the defender's means to reduce their own casualties. Similar to that of the attacker, the threshold that is identified for the communications latency is 1.5 to 2 minutes, as well. Both scenarios show that the defender has to exploit the characteristics of the terrain to his advantage. In the UO scenario, the cover afforded by the terrain is identified as the main terrain characteristic important to the defender, suggesting that the cover provided by buildings in an urban area is an advantage that the defender must exploit. In RCO, concealment is identified as the key characteristic. This suggests that the defender, where possible, will need to exploit the terrain concealment to hide the locations of his reserves to avoid being targeted by the attacker's artillery.

2. Impact of Terrain on Performance

From the data, we can see that in a UO, the chances of success for the attacker across a spectrum of capabilities and terrain conditions are at 26%. This is much lower when compared to that of the RCO, which stands at 52%. Mission success is defined as attriting more than two-thirds of the defender's forces, while retaining at least one-third of the attacker's force to ward off subsequent counterattacks by the defender.

The force exchange ratios for both the scenarios also support the findings. In the urban scenario, the attacker-defender mean force exchange ratio is 1.5 (1.5 attacker casualty for every defender casualty). For the RCO, that stands at a lower mean of 1.0.

C. ADDITIONAL INSIGHTS

In addition to the addressing the research questions, this thesis produced further insight as well. This section briefly summarizes the additional insights that were gained.

1. Attacker – Advance Only As Fast As Sensor-Shooter Cycle

Both scenarios revealed that where the sensor-shooter chain is slow (high latency), the attacking forces should advance slowly. When there is high latency, the defender's

reserves will not be well targeted, and a significant number will leak out and deploy at the frontal positions. This tactic allows the defender's reserves to be drawn out and deployed, thereby exposing them to targeting at their final deployed positions. Once the positions are "softened" by targeting and fires, the attacker will be able to capture these positions with less resistance.

2. Attacker – Communications Jamming

In both scenarios, we see that communications latency is one of the few factors that the defender is in control of in determining battle outcome. We can see that jamming of the defender's communications can be an effective method in blunting one of the few sources of strengths of the defender.

3. Attacker – Sensors That Can Penetrate Foliage

From the analysis, it revealed that in the river crossing scenario, the attacker's sensors are only effective when the concealment afforded by the terrain is lower. This suggests that sensors that are able to overcome foliage can be an important enabler for an effective targeting capability.

4. Defender – Employ Armored Reserves

From the analysis, it revealed that the defender's reserves have a decisive impact on the battle outcome. We can see that where targeting is ineffective, the attacker's casualties always increase due to the need to capture a better defended position. With that as a background, we can conclude that if the survivability of the defender's reserves can be increased by deploying them via armored carriers, it will take the attacker a lot more targeting effort and direct hits on the reserves to render them ineffective.

5. Simulating Operations

The advantage of computer simulation is the ability to cheaply and quickly simulate numerous types of large scale operations without placing any soldier at risk. In addition, computer simulation allows us to evaluate the effectiveness of new systems that are not yet developed and provide insights into how these new systems can be operated

alongside existing systems. TTPs of these new systems can be easily studied using computer simulation. This thesis simulated 2,570 UOs and 257 RCOs in different terrain conditions and capability settings. The analysis of these results reveals lessons learned for these operations that would be costly in terms of money, time, and casualties in real life.

6. Limits of Agent-Based Model (ABM) – MANA 4.0

Through the use of rapid scenario generation, which provided the avenue for exploring one of biggest models ever attempted in MANA, this thesis was able to push the limits of MANA. It is found that MANA would not be able to handle a model that is beyond 1,000-plus agents and 2,000-plus communications links. When translated to force sizes, this means approximately a brigade-plus-sized scenario is the maximum MANA can handle. Beyond this size, first it would take a very long time to complete a single run and second, the user runs the risk of MANA running out of memory.

D. RECOMMENDATIONS

The results of this thesis support the following recommendations:

- It is recommended that for armor to be effective, it will need to be able to withstand or deflect at least three antitank hits.
- For targeting to be effective, the sensor latency in transmitting information to the artillery units will have to be less than 1.5 to 2 minutes.
- For sensor latency that is higher than 1.5 to 2 minutes, the attacker will have to advance at a much slower pace.
- In a river crossing operation, sensors that are able to penetrate overhead concealment (such as foliage from the vegetation) are important enablers for good targeting capability.
- The attacker can improve his chances of success by jamming the defender’s communications prior to and during the capture of the objective.
- The defender should improve the communications responsiveness of his forces. This can be achieved via better communications equipment and/or better training, to ensure that battlefield information is delivered promptly.
- The defender should exploit the terrain characteristics to his advantage. Specifically, for UO, this is cover. For RCO, it is concealment for his reserves.

- The defender's reserves have a significant impact on the battle outcome. Improving the survivability of these reserves, such as by using armored carriers to transport them, can increase the defender's chances of success.

E. FURTHER RESEARCH

The following items are identified as areas warranting further research in:

- Continuing with more replications on both of the scenarios to obtain conclusions that can be statistically stronger.
- Explore the effects of different force structures. This can be done by reducing or increasing the force size.
- Human intangibles, such as aggressiveness and teamwork, can be further explored to understand their impact on battle outcome at the systems level.
- Expanding the scenario size of the urban scenario to a larger size at the brigade level.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A. THE RAPID SCENARIO GENERATION (RSG) TOOL

This chapter describes how the RSG tool that is developed can be used. This tool is not necessarily useful for all MANA users. For users looking at small models, it is better to do it manually, as it may involve more work using the RSG tool. It covers the necessary steps to generate a huge scenario. This step-by-step instruction contains four sections (A-D).

A. CREATE MODEL COMPONENTS IN MANA 4.0

One of the first steps would be to create all your individual model components in MANA first. This step is important as it also allows for a pseudo-testing of the individual components' behavior, and allows the modeler to see if the particular is behaving in the intended manner. Four types of MANA model files need to be created, each containing waypoints, generic behavior squads, communications squads, and lastly, the base scenario file, respectively.

The waypoints MANA file contains all the possible planned manners in which the agents can move within the scenario map. The generic squads MANA file contains all the types of squads that you have within your scenario (for instance, infantry, tanks, etc.). The communications squad MANA file contains all the different communications characteristics that will be assigned to different types of forces within your scenario. The base scenario file is derived from the MANA scenario file and can be created by just manually editing the XML file and deleting all squads from the file. The base scenario file is the file in which all the squads will be inserted into.

Once the three different types of MANA files are defined, the next step is to export the three different types of squads (waypoints, generic squads and communications) to three different folders. Before the squad files are exported, there are a few requirements that should be met:

- **Unique Communications Link** – For a communications squad, there should only be one type of communication link that the user would like to use. Multiple links will result in a program error.
- **Unique Squad Name –** Each of the squads should have a unique name. A nonunique name will result in the wrong squad being replicated.
- **No Communications Links in Noncommunications squad files –** In generic squad files and waypoint files, there should not be any communications links.
- **No Squads in Base Scenario File –** As mentioned, this base scenario file can be created by just taking any one of the three files (waypoints, generic squads, communications) and deleting all the squads from it.

From MANA, this could be exported from one of the drop-down menus using the "Save All Squads." A screenshot of that window is as shown in Figure 43.

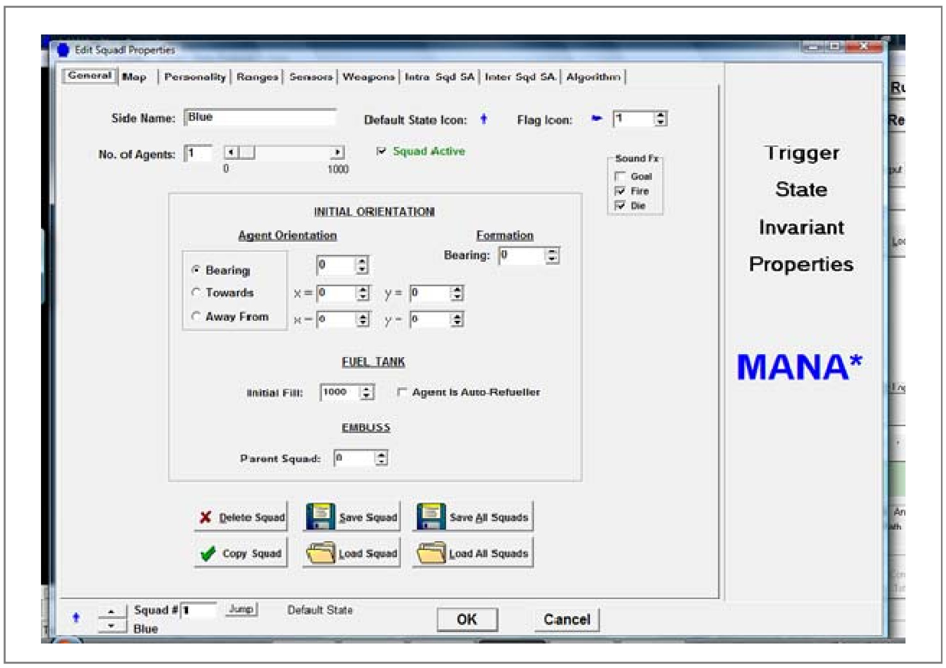


Figure 43. Screenshot from MANA on Exporting Individual Squads

B. RAPID SCENARIO GENERATION (RSG) EXCEL INTERFACE

With the basic component model files (base scenario, waypoint, generic squads, and communications) done, the next step is to import all the component files into the tool for generation of the MANA scenario file. This section explains the graphical user interface (GUI) of the RSG tool and the steps in using it to generate a scenario. The user

must ensure that the macro security settings are set to low and all macros are enabled for the scenario. This step is required so that the VBA code in the Excel sheet can work.

There are two main parts to the tool, the first is for the importing of data into the generator and the second is for the user to create his scenario. Figure 44 shows the user-interface for the importing of squad files.

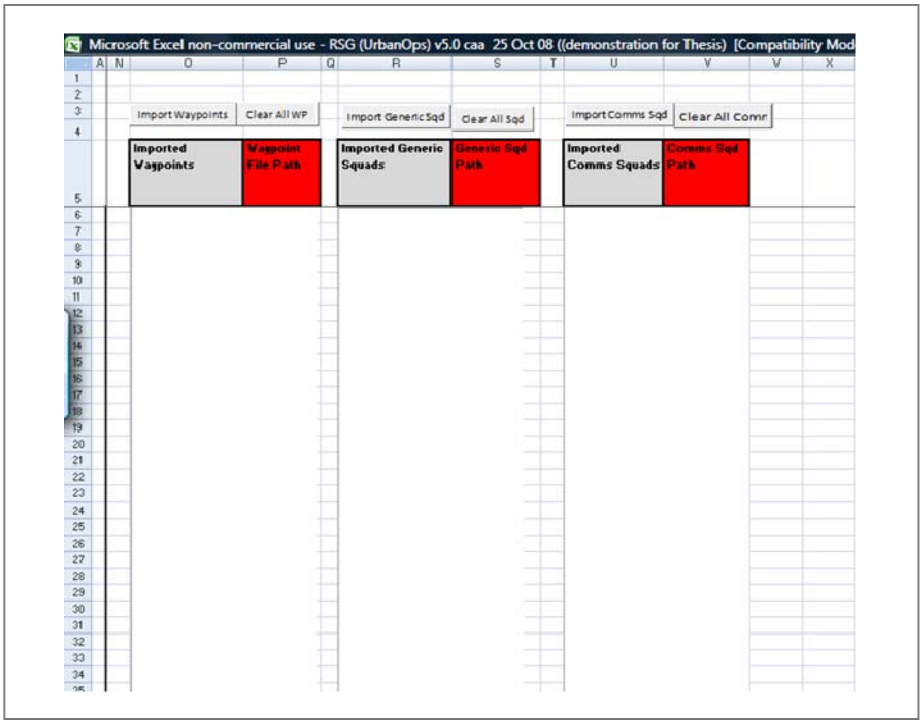


Figure 44. User-interface for importing of squad definition files

Each time before importing the squad files for a new scenario, click on the "Clear All" button for each of the three categories of squads. With that, click on "Import" for each of the categories to get the files required. The user will be prompted to select the directory and the files required for import. Multiple files can be selected by clicking and dragging of the mouse cursor over the files required at the directory. Figures 45 and 46 show the pop-up screens for importing of squad definition files.

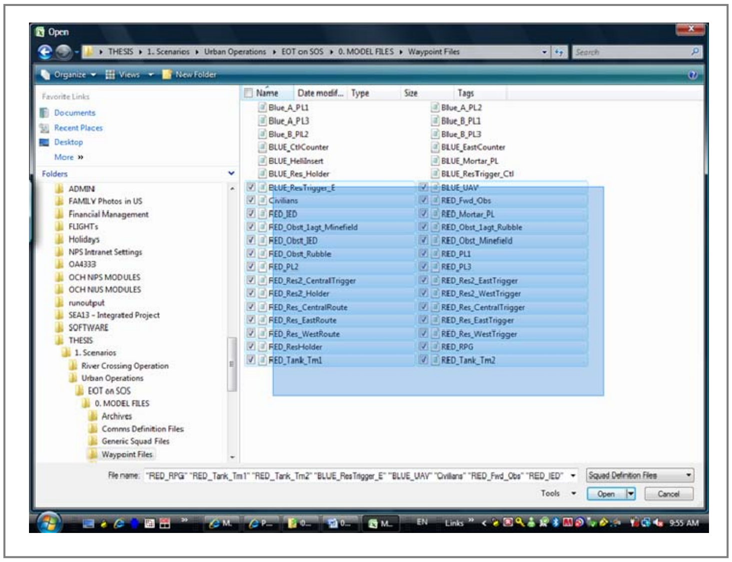


Figure 45. User-interface for importing of squad definition files (pop-up screen)

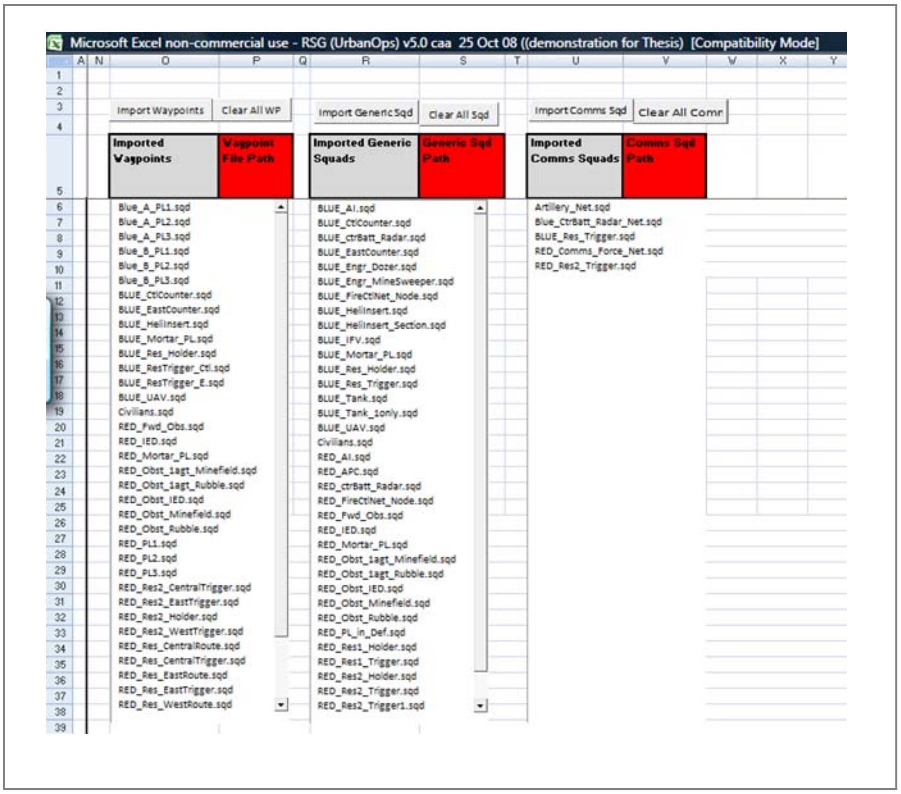


Figure 46. User-interface for importing of squad definition files (pop-up screen)

Once the files are imported, the interface will look like Figure 46. The next step is the design of the scenario. Figure 47 shows the user interface for the design of the scenario.

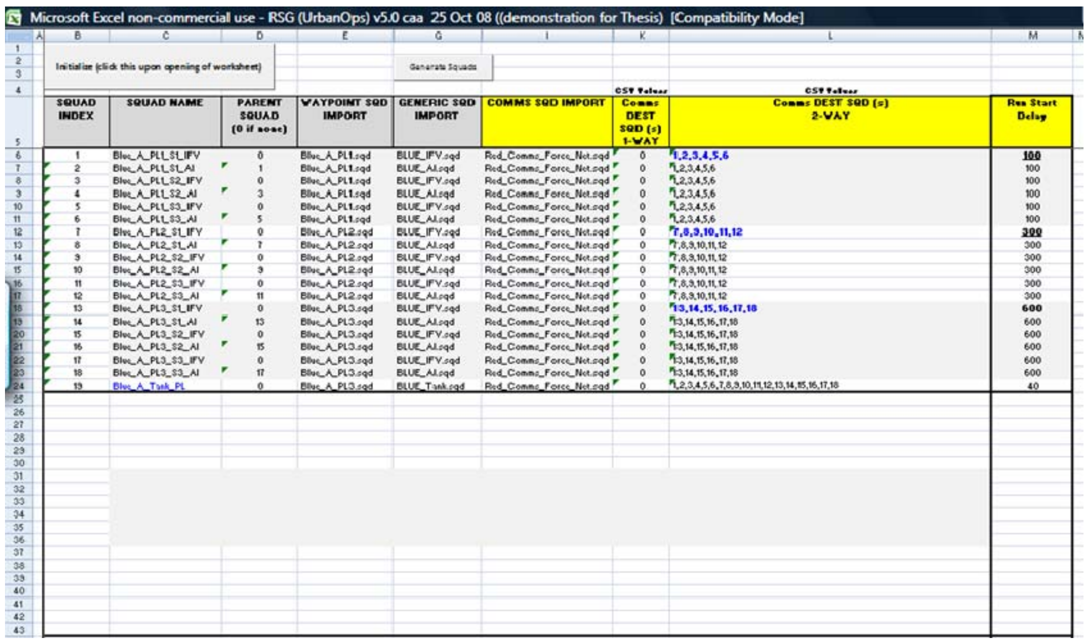


Figure 47. User Interface for Design of Scenario

The entries for the various columns shown in Figure 47 will need to be filled in. The columns' functions and input requirements are as specified in Table 9.

S/N	Column Name	Function	Remarks
1.	Squad Index	Squad ordering numbering that is referenced within MANA.	Ensure that all the numbers are in ascending order. Any repeated number will cause an error
2.	Squad Name	Name of the particular squad that you are creating	Ensure that there is no repeated name within the entire column.
3.	Parent Squad	Specifies which squad is its parent.	The specification is referenced by the squad index. 0 if there is no parent.
4.	Waypoint squad	Specifies the waypoints of the	There is a drop-down menu

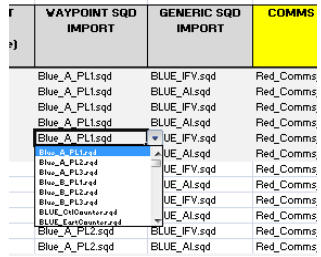
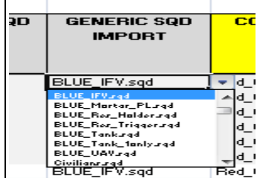
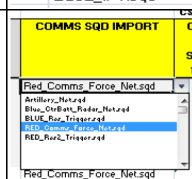
S/N	Column Name	Function	Remarks
	import	squad that will be created.	within each cell in this column. Select it from the drop-down  menu.
5.	Generic Squad Import	Specifies which type of squad it is. Similar to the waypoint import, it can be selected from a drop down menu within each cell.	
6.	Communications Squad Import	Specifies which type of communications link is being employed by this squad. Similarly, select the type from the drop-down menu.	
7.	Comms Dest Sqd(s) 1-way	Specifies which squads it is communicating with. This is a one-way communication mode only, i.e., the squad will only send messages to the specified squad, it will not receive any messages from the destination squad.	The destination squad is referenced by the squad index. The formatting of the input is by the use of comma separated values (csv). Hence, if the destination squads are 3, 4 and 5, the input would be 3,4,5.
8.	Comms Dest Sqd(s) 2-way	Specifies which squads it is communicating with. This is a two-way communication mode only, i.e., the squad will only send messages to the specified squad, it will not receive any messages from the destination squad.	
9.	Run Start Delay	Specifies the time for the Run Start state of the MANA 4.0. This allows the user to decide the time at which the squad is activated to start moving within the scenario.	For this option to be applicable, all the generic squad files that are modeled will need to have the Run Start state selected.

Table 9. RSG Tool Scenario Generation User Interface Column Description

If there is a need to increase the number of row entries, the entire row should be copied and paste to create the next row. The reason is that there are hidden columns within the excel sheet that references the paths of the corresponding import files for generation for the MANA scenario file. The failure to do so will result in an error.

After all the squads that have to be generated are ready, the next step is to hit on the "Generate" button. This will set off a series of prompts to the user to create his scenario file. The prompts are described as follows.

Figure 48 shows the first prompt to the user to select the directory to save the individual squad files that will be generated.

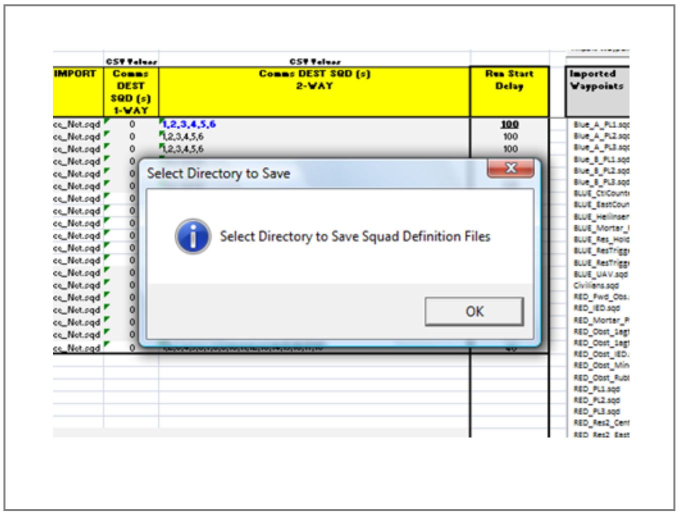


Figure 48. Generation of MANA Model File Prompt 1

Figure 49 shows the second prompt requires the user to specify the base scenario file that was previously created.

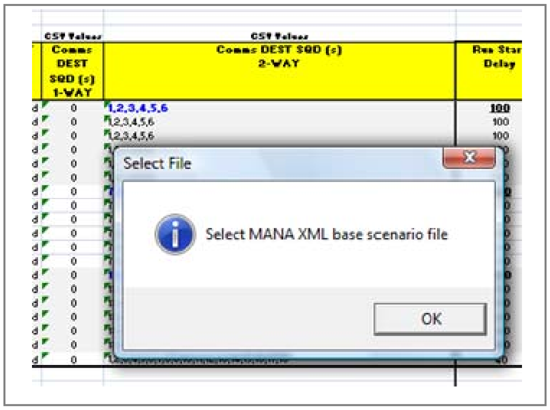


Figure 49. Generation of MANA Model File Prompt 2

Figure 50 shows the third prompt requires the user to specify where he would like the final scenario file to be generated for subsequent retrieval.

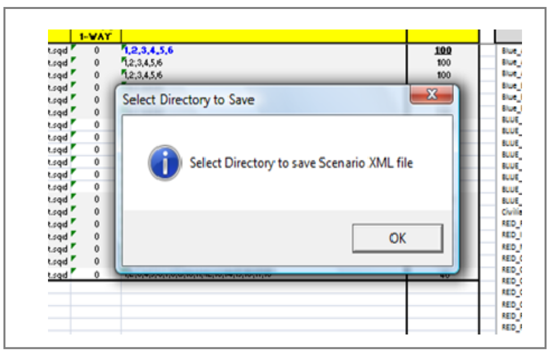


Figure 50. Generation of MANA Model File Prompt 3

Once the scenario file is successfully generated, a final pop-up message, as shown in Figure 51, will come up informing the user of the successful generation of the scenario file. The user can then proceed to retrieve the file from the directory that was previously specified.

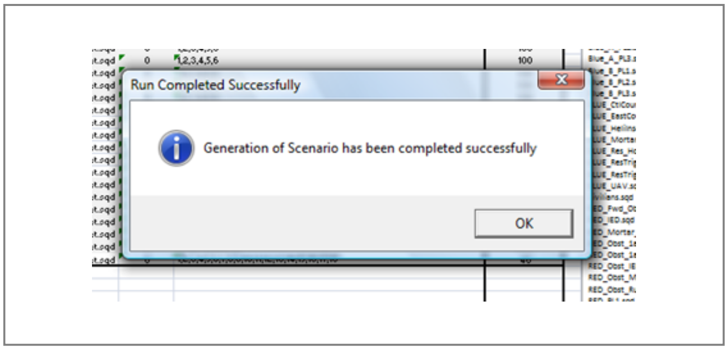


Figure 51. Generation of MANA Model File Successful Generation Prompt

C. RAPID DESIGN OF EXPERIMENTS (RDOE) INTERFACE

A large scenario will also require the ability to rapidly create design of experiments. The study files will require the user to specify the characteristics of the squads that are to be varied in accordance with the design of experiments. This tool will allow the user to create large study files in fractions of a second. The interface and how the study file can be generated are described here. A screenshot of the interface is as shown in Figure 52.

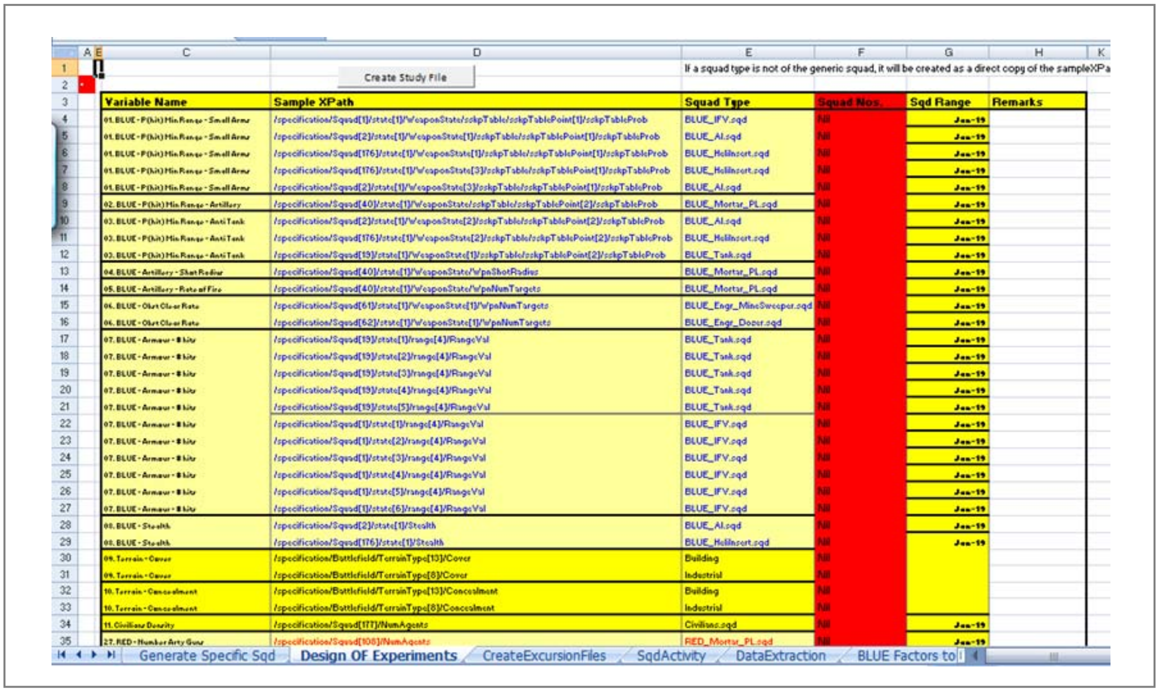


Figure 52. Screenshot of the Rapid Design of Experiments Tool

The first step of the rapid design of experiments tool is to set up an empty study file so that the study paths can be filled. This is achieved using the XStudy tool that was developed by Steve Upton, Research Associate at the SEED Centre. Inside this empty study, the user needs to specify the inputs like the name of the design of experiments csv file, his name, etc. The variables to be varied will not need to be specified, since they will be generated by the RDOE tool.

The columns of the rapid design of experiments tool is described in Table 10.

S/N	Column Name	Function	Remarks
1.	Variable Name	Specifies the name of the variable that you are varying.	
2.	Sample XPath	Specifies the XML path in which the variables will be varied.	This can be obtained from XStudy 1.0 by checking the path that will be varied. A sample of input is **/specification/Squad[19]/state[1]/range[4]/RangeVal** This path essentially changes the number of hits a particular agent can sustain before being killed.
3.	Squad Type	Specifies the generic squad type.	The input for this must correspond with that found in the column for the generic squad import column of the rapid scenario generator tool. A sample input will look this: **BLUE_IFV.sqd**
4.	Squad Numbers	Specifies the squad index that is relevant to the squads whose parameters will be varied.	This column is highlighted in Red and should not be modified by the user at all. The background VBA routine will generate the inputs required for this column.
5.	Squad Range	Specifies the squad indexes that will be searched for the relevant squad type.	This specifies the squad ranges to look at. For instance, you may want to vary the characteristics for a certain group of tanks but the others. This feature will allow you to do that.

Table 10. Rapid Design of Experiments (RDOE) Tool

Once all that is done, click on the “Create Study File” button and the user will be prompted to select the empty study file. The caption is named “Select MANA XML base scenario file.” The screenshot of the prompt is as shown in Figure 53.

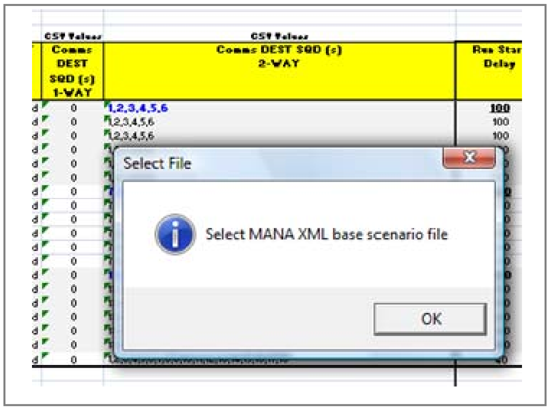


Figure 53. Generation of Empty Study File

Once the user selects his empty study file, the study file will be created in a very short period time with the following confirmation shown in Figure 54.

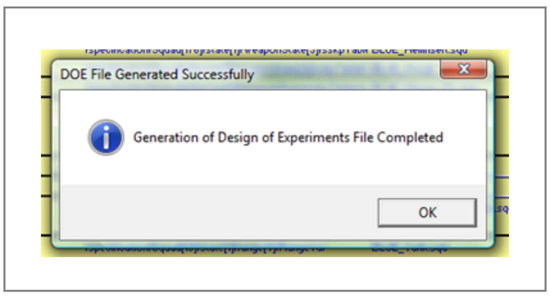


Figure 54. Confirmation on Successful Generation of DOE File

The empty study file will then be over-written with the additional information from the DOE file. The user can then extract the file from that location and submit it for runs on the cluster.

D. GENERATION OF INDIVIDUAL EXCURSION FILES

This section describes how the user can generate individual excursion files from the design of experiments file (which consists of all the design points). This allows the user to be able to play back individual files, and observe how the simulation plays out visually, when there are unusual or unexpected findings in the output data that can only be confirmed and better understood if it is actually seen.

In addition, this also provides users the option to run the individual design points from their own machines if a cluster is not readily available.

This tool is particularly flexible as it does not require it to be a MANA model. As long as the model defined using an XML file, it will be able to generate individual files. This tool requires three types of files: the DOE csv file, the Study file in Old McData format, and the model scenario XML file.

Figure 55shows the layout of the Excursion File Generator. It is located in a "Create Excursion File" sheet with only one button. By clicking on the Generate Excursion File button, the user will be guided through a series of steps to generate the excursion files.

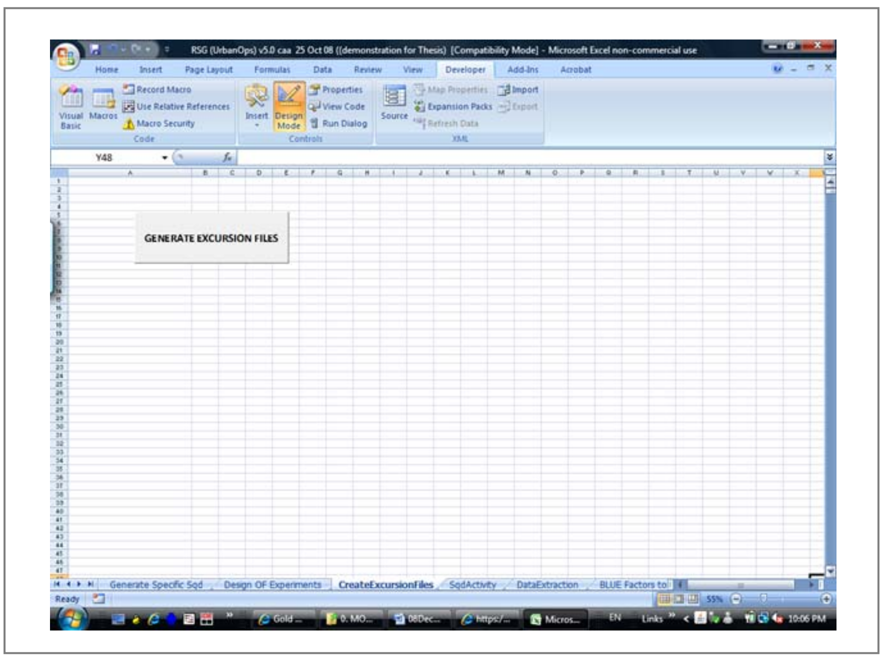


Figure 55. Screenshot of the Layout of the Excursion File Generator.

As shown in Figure 56 the first prompt involves the user specifying the design of experiments file.

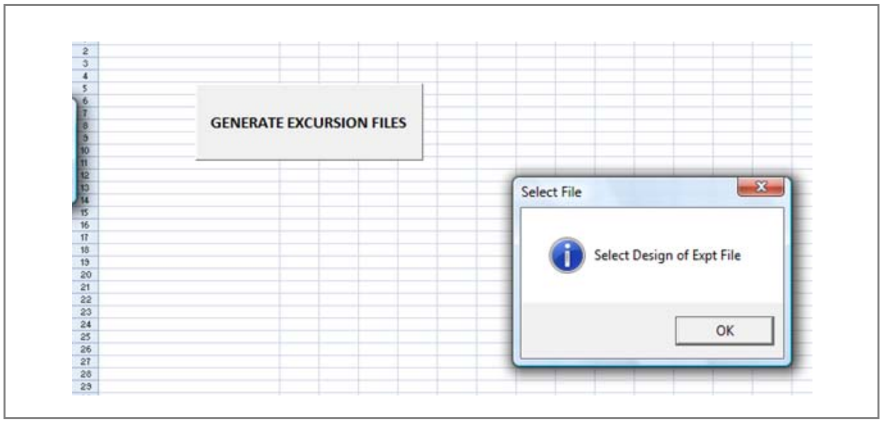


Figure 56. Excursion File Generator Prompting for Design of Experiment File

Figure 57 shows the prompt request for the second file, which involves the specification of the model scenario file. This is where the values are to be varied in accordance to the design of experiments file.

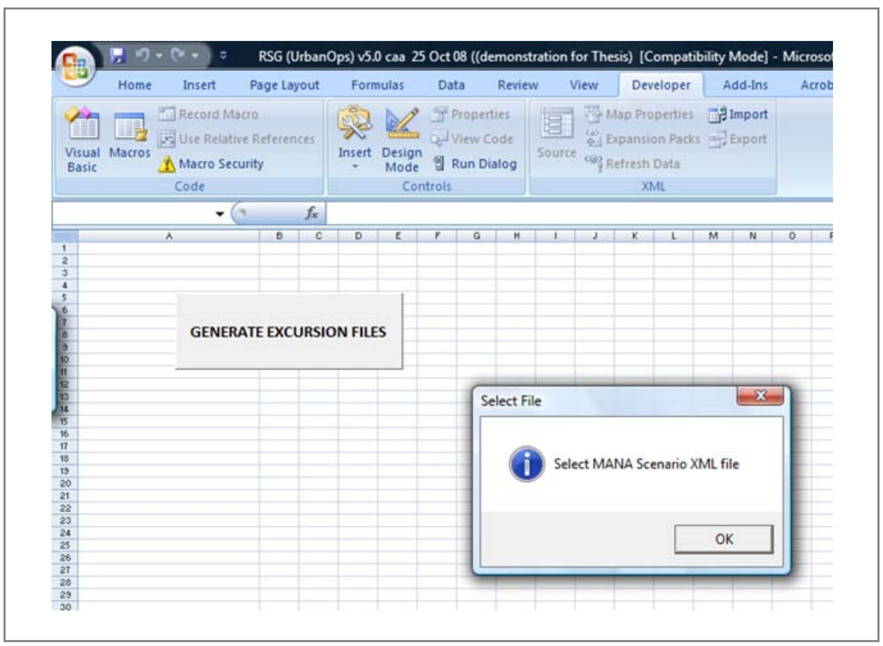


Figure 57. Excursion File Generator Prompting for Scenario File

The third prompt, shown in Figure 58 requires the user to specify the location of the Study file.

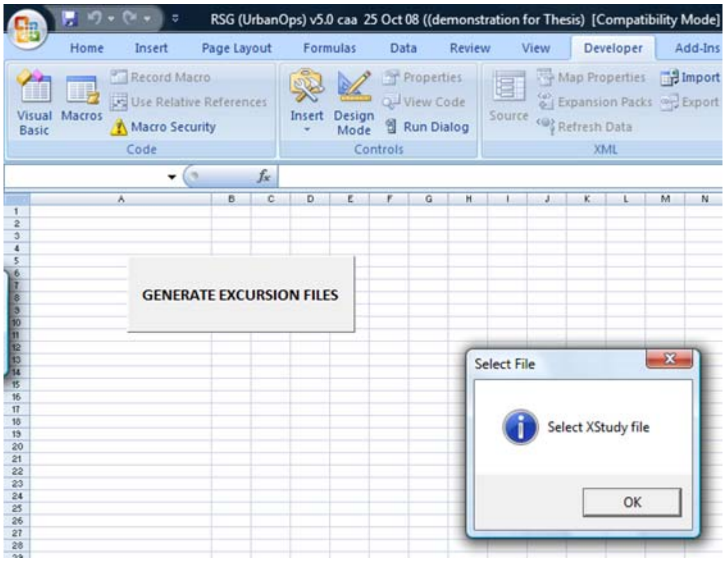


Figure 58. Excursion File Generator Prompting for XStudy File

The final prompt, shown in Figure 59 requires the user to specify where the excursion files will be saved. After this step, the excursion files will be generated and the user can proceed to the specified directory to retrieve the required files.

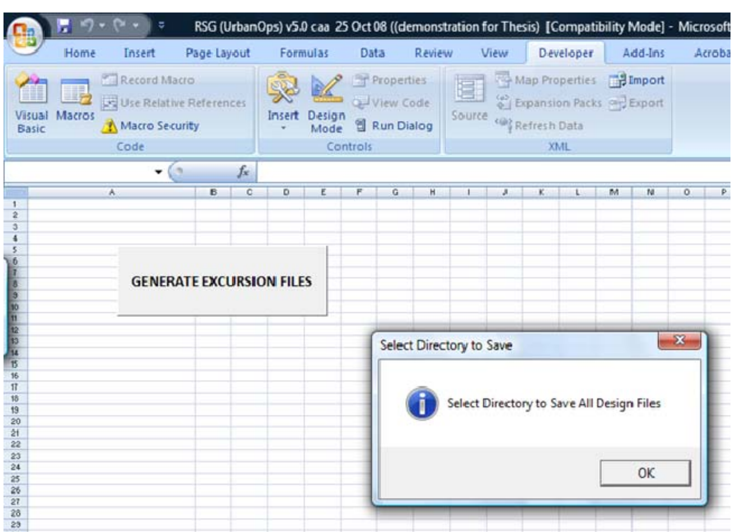


Figure 59. Excursion File Generator Prompting for Location to Save All Excursion Files

APPENDIX B. DETAILED DESCRIPTION OF MODEL COMPONENTS

This appendix explains in detail the behavior of the various generic squad types and how they interact in relation with one another. State transition diagrams detailing how agents behave and the event that triggers state changes is the primary mechanism to achieve this. It covers how the various systems behave. For instance, the obstacles' effects, river crossing, and the reserve activation subcomponents are covered in detail. There are three main parts to this appendix: the modeling obstacles, the reserve activation system, and the river crossing system.

A. OBSTACLES

This section covers how obstacles are modeled. MANA does not have the ability to model obstacles explicitly. Some modeling techniques exploiting the various features of MANA have to be employed. In this instance, we use the refueling feature to model obstacles. All agents that are subject to the effects of obstacles need to have the "Refuel by En Type 1" trigger state enabled. As described in Chapter II, three types of agents are classified in this model:

- Threat 1 – Obstacles
- Threat 2 – Troops/Soldiers
- Threat 3 – Vehicles (includes soft-skinned and armored vehicles)

In this instance, we will set only vehicles to be subject to the influence of obstacles, since the primary purpose of obstacles is to stop vehicles and not dismounted troops. This means that only vehicular agents have the "Refuel by En Type 1" trigger state enabled, with the additional settings of (highest priority, cannot interrupt, interrupter) for the trigger state. For the agents subject to the effects of obstacles, upon being refueled by the obstacle agents, their movement speed will be zero. For these agents, they can have additional other states that will reflect the character and personality of the type of force it is representing.

To model obstacles that will inflict damage on agents that approach them if they are close enough (e.g., mines), the obstacle agent can be equipped with an additional weapon that will shoot the agents that approach within the "weapon" range. For the obstacle agents, under the "Range" settings for the obstacle agents in MANA, the following settings will apply:

- Refuel Trigger Range – 5
- Prob Refuel Enemy – 100

Other than being stopped by obstacles, there will be a need to create agents that are able to clear the obstacles. In actual operational conditions, this is carried out by combat engineer forces. The obstacle clearing agents need not be necessarily stopped by the obstacle agents. If they are infantry, they will not be stopped, but if they are vehicular, they will be stopped. These obstacle-clearing agents will be equipped with weapons that will specifically target only the obstacles that they can clear; it will be useless against other types of obstacles.

The state transition diagrams for the modeling of obstacles and obstacle-clearing agents are shown in Figure 60.

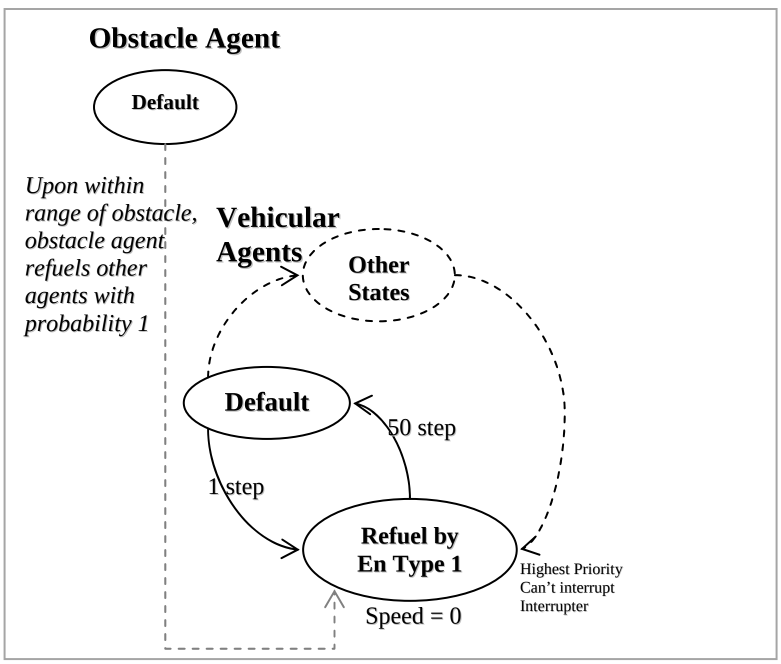


Figure 60. State Transition Diagram for Modeling Obstacles Effects

B. RESERVE ACTIVATION SYSTEM

This section covers how reserves are activated within the model. The main purpose of modeling the reserves' behavior is to model the effect of forces with the flexibility to be deployed to areas where they are most required. In this thesis, there are sets of reserves that will be deployed at two different times, depending upon the triggers that will activate. The key idea behind modeling this is first to create n sets of forces with respect to n routes to be taken. For instance, if a platoon-sized reserve may be activated to reinforce via one of the three sets of routes, then there is a need to create three sets of platoon-sized reserves.

With that, create three holder agents that will each hold one of the platoon-sized reserves. These holder agents are modeled as not visible to any agent and invulnerable. There will be a trigger agent that is located on the battlefield that provides information on enemy forces. If it senses enemy forces coming in that direction; it will send information to the holder agent to activate the reserves. The holder agent that is first activated to release the reserves will "refuel" the other holder agents and prevent any subsequent release of additional reserves. We will take a look at the state transition diagrams in Figure 61 for activating reserves along either of two possible routes in two pieces.

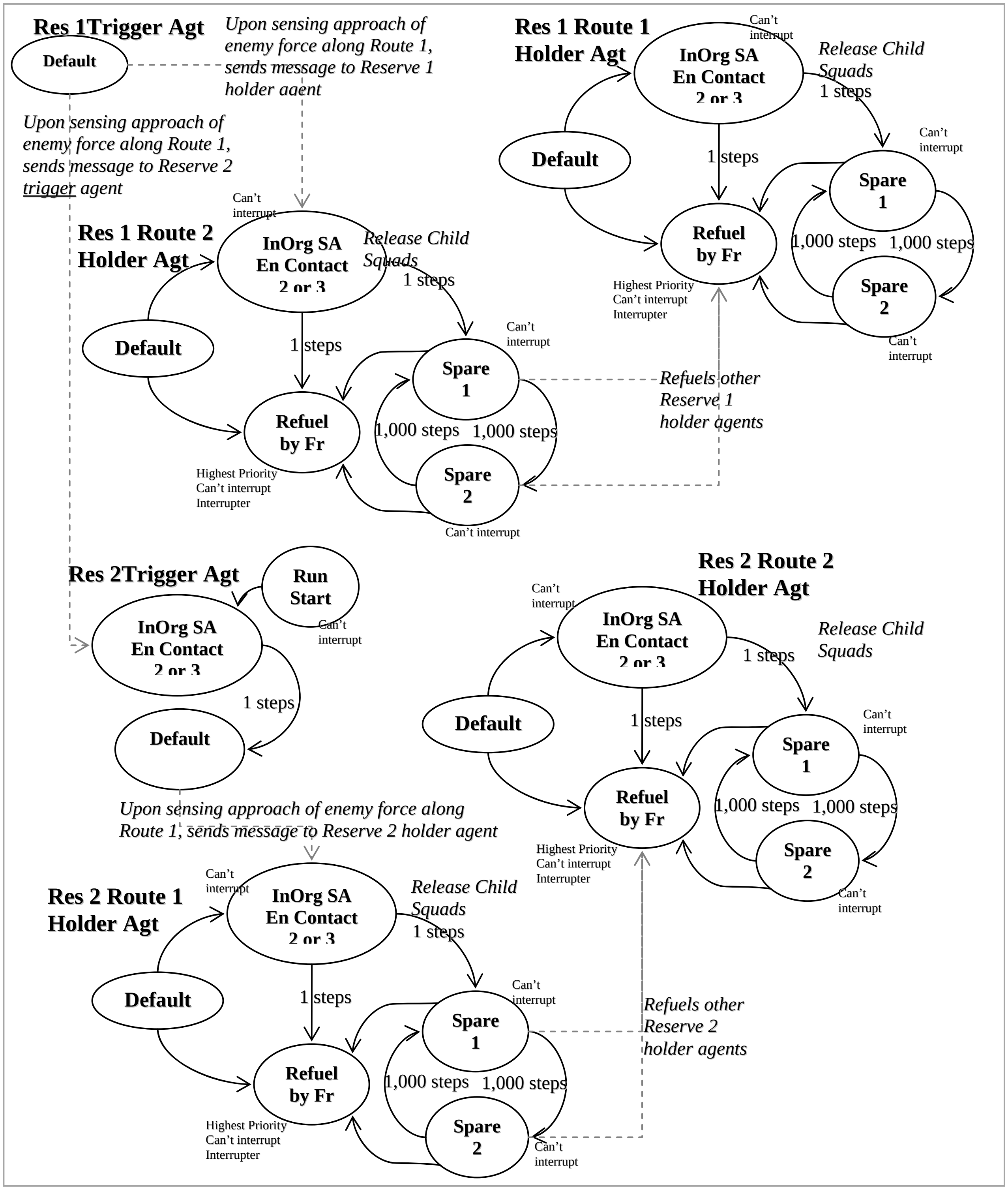


Figure 61. State Transition Diagram for Reserves Activation System

C. RIVER CROSSING SYSTEM

This section covers on how the river crossing is modeled. One of the challenges in modeling of the river crossing is the modeling of the process of vehicles loading and unloading onto rafts. Vehicles will not be able to cross the river when there are no rafts.

The agents that will need to be created and their purpose are listed in Table 11.

S/N	Agent Type	Purpose	Remarks
1.	Beach strip trigger agent	Upon capture of the beachstrip (own forces reach within sensor range), the agent indicates that it is captured by changing state to a "neutral" agent.	Communications links with ERP regulator agent and Raft agent(s) Allegiance = 0 (neutral agent) Armor = 100
2.	Beach strip comms agent	Co-locates with the beach strip trigger agent, sends information on the beach strip trigger agent to the raft agents and also the ERP regulating agent.	
3.	Crossing site stopper agent	Stops the vehicles from crossing the river when there is no raft available to bring the vehicles across.	Communications link with ERP regulator agent
4.	Crossing site trigger info agent	This agent provides information to the ERP regulating agent when there is an available raft. Once an available raft reaches the site, it will be refueled by the raft and it turns to state "Neutral." This state transition will be sensed by the co-located Crossing site stopper agent which transmits the information to the ERP regulating agent to release vehicles to the site to cross the river.	
5.	ERP regulating agent	Regulates the number of vehicles that can "board" the raft each time, this is located at the assembly area at a distance from the crossing site. This is regulated by a weapon that "shoots" at vehicles waiting at the assembly area. It has a limited number of shots and reloads to release more vehicles when the next raft arrives.	
6.	ERP stopper agent	Stops the agent just before it is allowed to move to the crossing site along the river.	
7.	Raft agent	The raft agent acts as the "key" to opening the crossing site for crossing. Upon reaching the crossing site, it will "refuel" the ERP stopper	

S/N	Agent Type	Purpose	Remarks
		agent and it allows the vehicles waiting to cross to move through it.	
8.	Troop carrier agent	This is a surrogate agent that holds the actual vehicle that is crossing the river. This can only be done in MANA 4 since the embuss feature is only available in MANA 4. Once this surrogate agent crosses the river, it releases the vehicle it is holding, for the combat mission to continue. One surrogate agent is required for every vehicle that is crossing the river.	

Table 11. Description of MANA Agents for River Crossing System.

The state transition diagram for the entire model is shown in Figure 62 and 63.

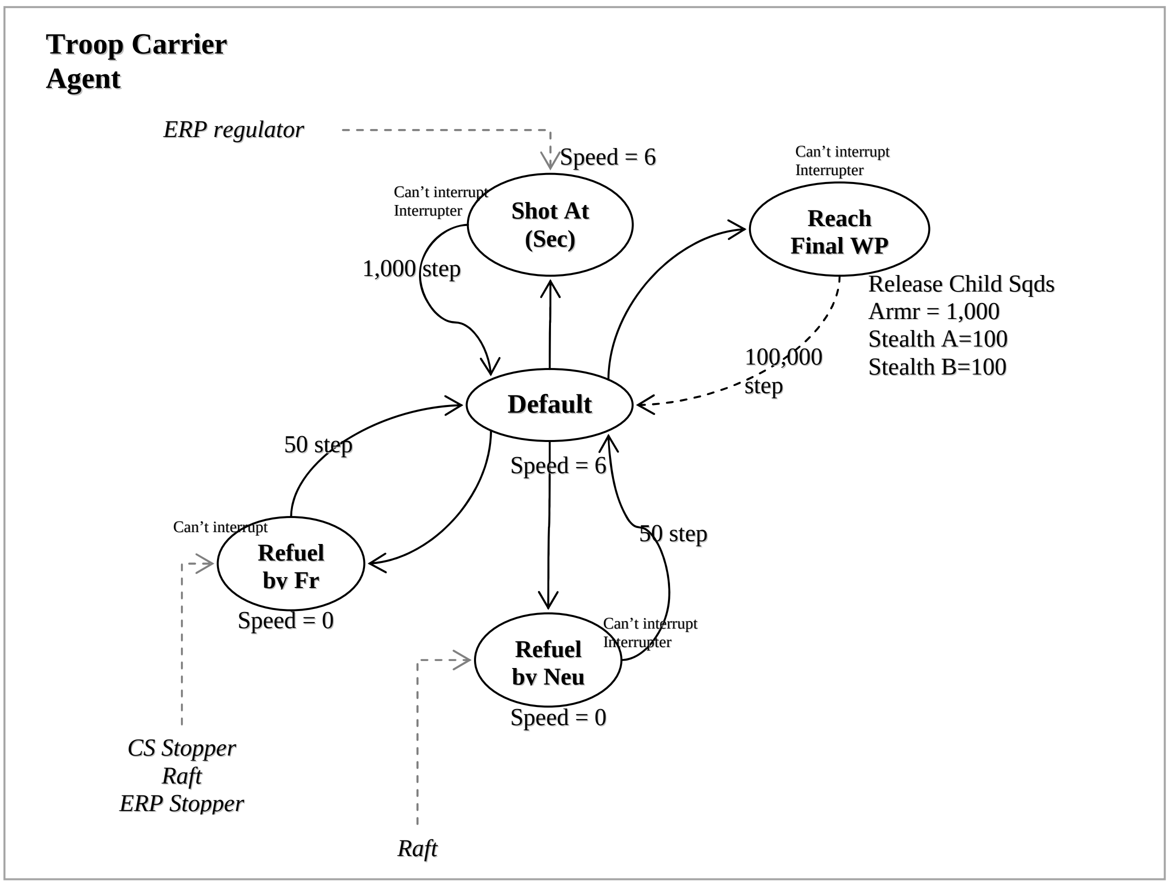


Figure 62. State Transition Diagram for River Crossing Part One

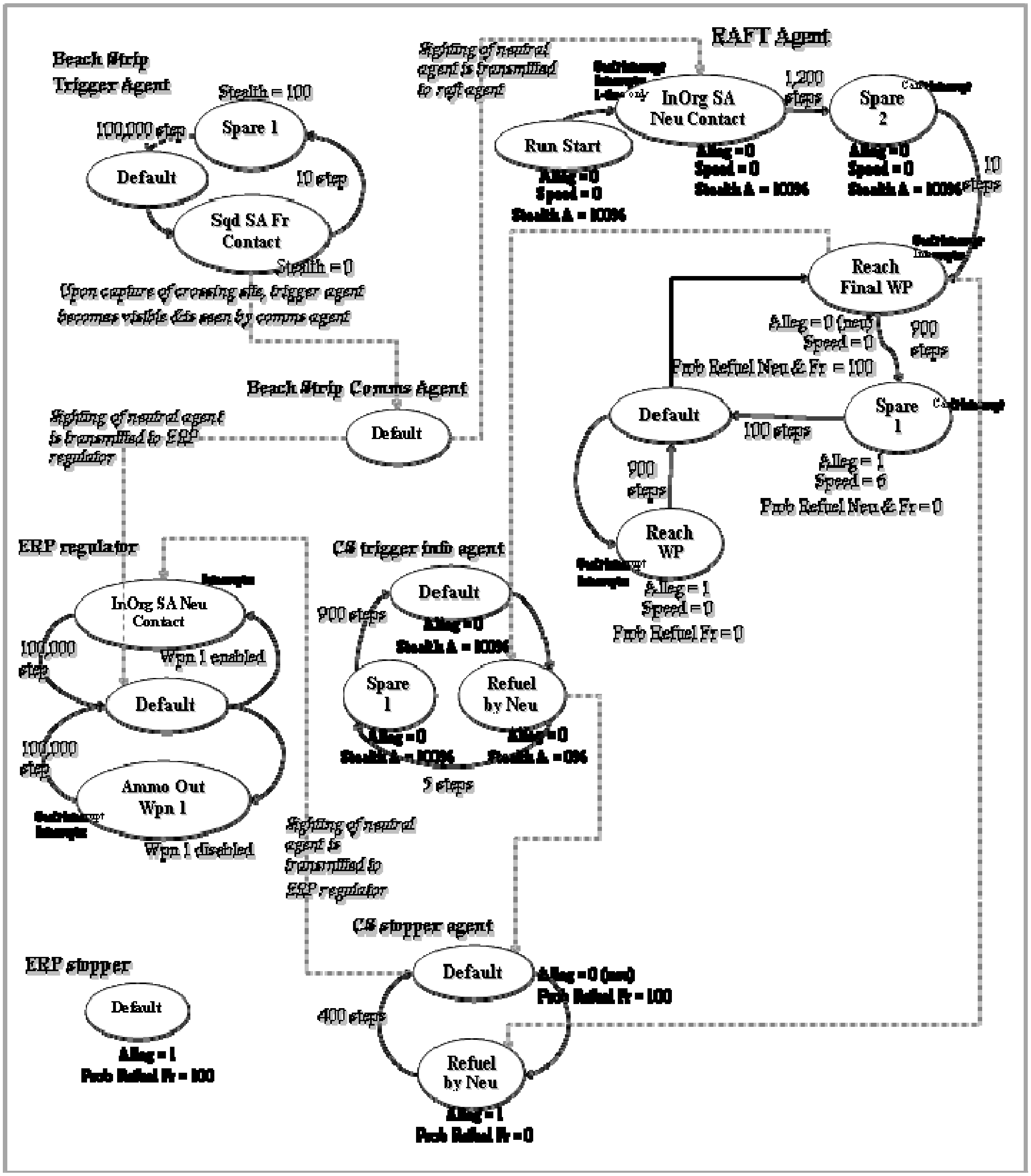


Figure 63. State Transition Diagram for River Crossing Part Two

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C. OUTPUT OF CLUSTER AND OUTLIER ANALYSIS

This appendix shows the detailed output results of COADM for both the urban and river crossing scenarios.

A. URBAN OPERATIONS (UO)

Figures 64 and 65 show the U matrix and the Hit map, respectively. Figure 66 shows the locations of the outliers in the respective clusters. Table 12 gives the detailed statistics of the respective clusters.

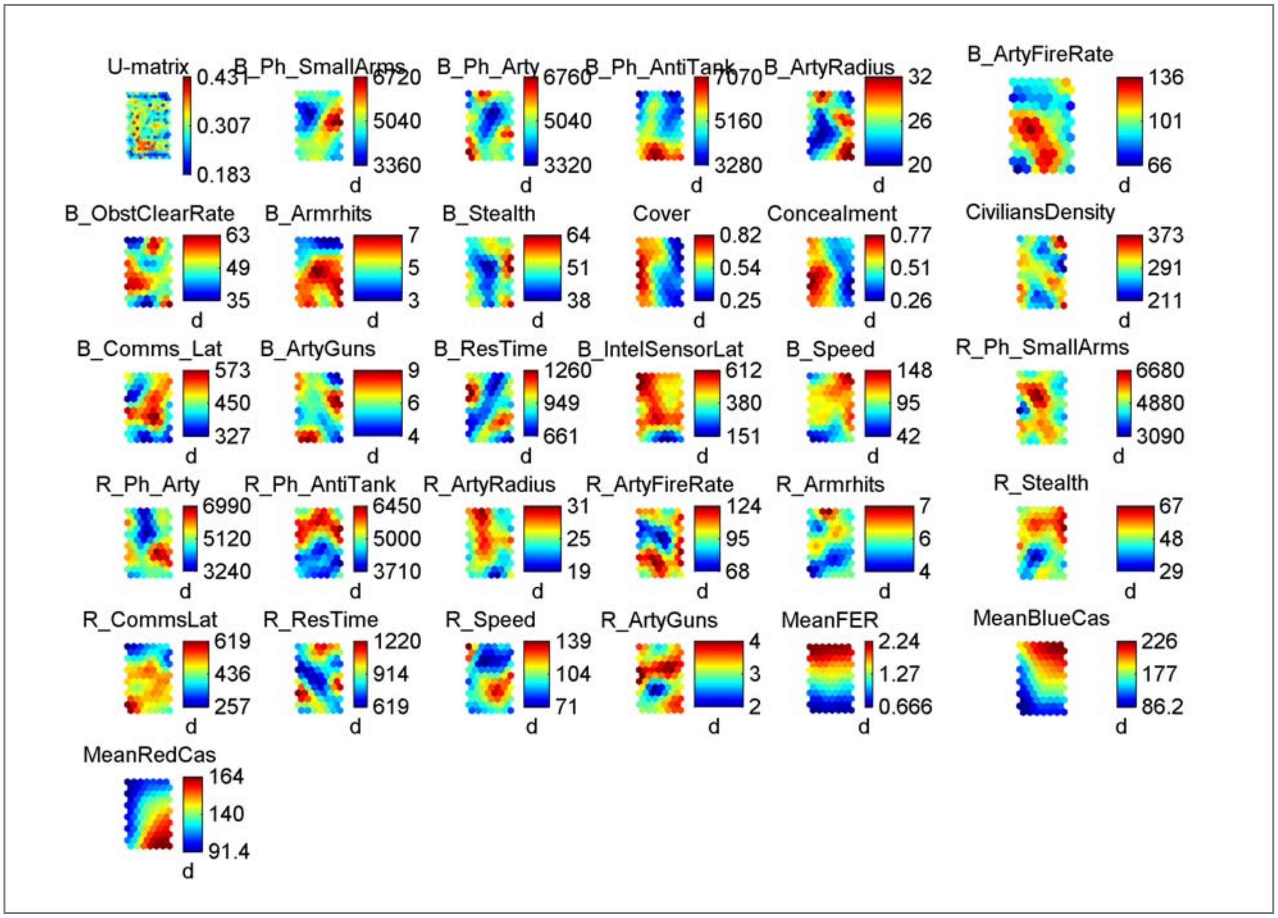


Figure 64. UO – U-matrix and Component Planes

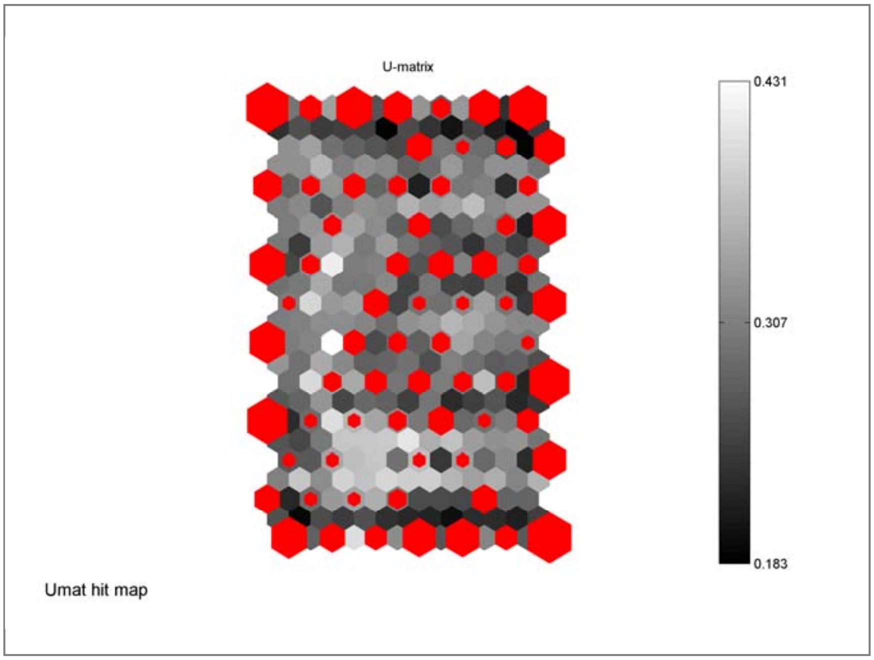


Figure 65. UO – U-matrix and Hit Map

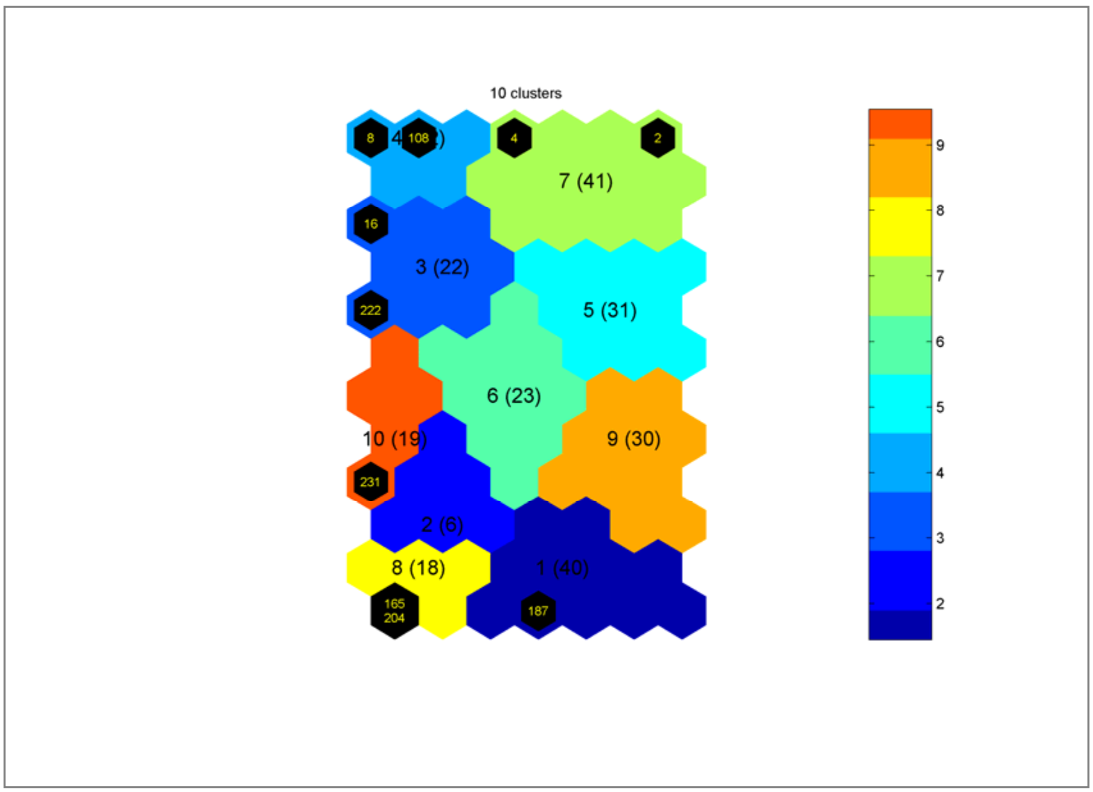


Figure 66. UO – Clusters and Outliers

1 MeanFER 0.832 +/- 0.255 MeanBlueCas 125.000 +/- 38.559 MeanRedCas 161.400 +/- 6.661 B_Ph_AntiTank 6328.000 +/- 2913.333 B_ArtyRadius 29.000 +/- 13.461 B_ArtyFireRate 114.000 +/- 61.646 R_ArtyFireRate 109.000 +/- 66.060 R_ArtyGuns 4.000 +/- 1.569 B_Armrhits 6.000 +/- 2.524 R_Ph_SmallArms 5274.000 +/- 2853.685 R_CommsLat 464.000 +/- 244.014 R_Stealth 50.000 +/- 31.233 R_Speed 103.000 +/- 55.992 R_Ph_Arty 5079.000 +/- 2808.235 B_Stealth 50.000 +/- 33.217 B_Ph_Arty 4922.000 +/- 2675.858 B_Ph_SmallArms 4883.000 +/- 2641.498 R_ResTime 872.000 +/- 579.251 B_ResTime 886.000 +/- 517.062 B_ObstClearRate 48.000 +/- 32.154 B_ArtyGuns 6.000 +/- 2.926 R_Armrhits 5.000 +/- 2.602 CiviliansDensity 277.000 +/- 187.103 Concealment 0.470 +/- 0.254 B_Speed 78.000 +/- 52.775 R_ArtyRadius 23.000 +/- 14.842 B_Comms_Lat 387.000 +/- 256.636 R_Ph_AntiTank 4337.000 +/- 2816.202 Cover 0.380 +/- 0.213 B_IntelSensorLat 260.000 +/- 182.875	2 MeanFER 1.012 +/- 0.343 MeanBlueCas 121.300 +/- 42.943 MeanRedCas 131.500 +/- 32.827 R_ArtyFireRate 117.000 +/- 54.482 Concealment 0.680 +/- 0.288 B_ObstClearRate 57.000 +/- 25.375 R_ResTime 1034.000 +/- 467.713 B_Ph_AntiTank 5899.000 +/- 2642.103 Cover 0.650 +/- 0.224 B_Armrhits 6.000 +/- 2.338 B_IntelSensorLat 492.000 +/- 318.668 B_ArtyFireRate 109.000 +/- 65.279 R_CommsLat 496.000 +/- 310.476 R_Ph_SmallArms 5352.000 +/- 2612.081 R_ArtyRadius 27.000 +/- 14.624 R_Ph_Arty 5274.000 +/- 2238.012 R_Speed 103.000 +/- 66.305 B_Ph_SmallArms 5040.000 +/- 3147.091 B_Speed 96.000 +/- 64.423 B_Comms_Lat 450.000 +/- 250.890 B_Ph_Arty 4961.000 +/- 2116.907 B_ArtyGuns 7.000 +/- 2.422 CiviliansDensity 281.000 +/- 130.083 B_Stealth 47.000 +/- 23.981 R_Armrhits 5.000 +/- 2.787 B_ResTime 809.000 +/- 446.499 R_Ph_AntiTank 4376.000 +/- 2906.742 R_ArtyGuns 3.000 +/- 1.169 R_Stealth 37.000 +/- 8.329 B_ArtyRadius 21.000 +/- 6.623
3 MeanFER 1.531 +/- 0.663 MeanBlueCas 174.900 +/- 46.947 MeanRedCas 105.300 +/- 26.261 R_Ph_AntiTank 5977.000 +/- 2358.601 B_ResTime 1083.000 +/- 339.192 Cover 0.700 +/- 0.248 R_Ph_SmallArms 5938.000 +/- 2831.438 B_IntelSensorLat 545.000 +/- 155.665 R_Stealth 56.000 +/- 30.828 R_ArtyGuns 4.000 +/- 1.649 R_ArtyRadius 28.000 +/- 14.516 B_Speed 109.000 +/- 49.056 Concealment 0.590 +/- 0.283 CiviliansDensity 302.000 +/- 172.709 B_ArtyGuns 7.000 +/- 3.457 R_CommsLat 454.000 +/- 247.937 B_ObstClearRate 50.000 +/- 27.289 B_Ph_Arty 4766.000 +/- 3196.673 B_Ph_AntiTank 4805.000 +/- 3382.685 B_ArtyFireRate 95.000 +/- 58.169 B_ArtyRadius 24.000 +/- 16.340 B_Armrhits 5.000 +/- 1.965 R_Ph_Arty 4649.000 +/- 2725.210 R_Armrhits 5.000 +/- 2.304 R_Speed 90.000 +/- 60.677 B_Stealth 45.000 +/- 27.825 R_ResTime 745.000 +/- 566.458 B_Comms_Lat 380.000 +/- 230.418 R_ArtyFireRate 79.000 +/- 45.473 B_Ph_SmallArms 3829.000 +/- 3158.259	4 MeanFER 2.120 +/- 1.909 MeanBlueCas 197.200 +/- 35.031 MeanRedCas 95.700 +/- 27.305 B_IntelSensorLat 591.000 +/- 241.688 R_ArtyRadius 29.000 +/- 12.079 B_ArtyRadius 28.000 +/- 12.923 Cover 0.660 +/- 0.232 R_Armrhits 6.000 +/- 3.127 B_ResTime 998.000 +/- 490.703 R_Speed 110.000 +/- 70.701 Concealment 0.600 +/- 0.300 R_ArtyFireRate 104.000 +/- 48.939 B_ArtyGuns 7.000 +/- 2.759 R_ArtyGuns 4.000 +/- 1.352 R_Ph_AntiTank 5157.000 +/- 3137.316 R_Stealth 50.000 +/- 25.965 B_Ph_Arty 5118.000 +/- 3474.217 CiviliansDensity 288.000 +/- 177.038 R_Ph_SmallArms 4883.000 +/- 2554.980 R_ResTime 872.000 +/- 530.532 B_Stealth 49.000 +/- 24.013 B_Ph_SmallArms 4805.000 +/- 2863.704 B_Comms_Lat 436.000 +/- 230.413 R_Ph_Arty 4571.000 +/- 2558.947 B_Speed 79.000 +/- 52.982 B_ArtyFireRate 89.000 +/- 46.475 B_Armrhits 4.000 +/- 2.935 B_Ph_AntiTank 4102.000 +/- 2181.052 B_ObstClearRate 38.000 +/- 16.942 R_CommsLat 295.000 +/- 291.025

5 MeanFER 1.405 +/- 0.203 MeanBlueCas 200.700 +/- 12.434 MeanRedCas 143.300 +/- 12.322 B_Ph_SmallArms 5977.000 +/- 2735.220 R_ArtyGuns 4.000 +/- 1.620 R_Ph_AntiTank 5704.000 +/- 2190.233 B_ArtyGuns 8.000 +/- 3.098 B_ArtyRadius 28.000 +/- 12.953 R_Stealth 57.000 +/- 25.414 B_Speed 116.000 +/- 48.452 B_Armrhits 6.000 +/- 2.104 B_Comms_Lat 496.000 +/- 255.388 B_Stealth 54.000 +/- 25.667 R_Armrhits 6.000 +/- 2.642 R_ArtyRadius 26.000 +/- 15.215 R_CommsLat 468.000 +/- 261.447 B_IntelSensorLat 439.000 +/- 254.382 R_Ph_SmallArms 5118.000 +/- 3000.531 B_ObstClearRate 48.000 +/- 26.399 R_ArtyFireRate 92.000 +/- 56.971 R_ResTime 844.000 +/- 493.297 R_Ph_Arty 4688.000 +/- 3141.539 R_Speed 96.000 +/- 55.171 B_ResTime 865.000 +/- 462.445 B_ArtyFireRate 92.000 +/- 61.443 Cover 0.400 +/- 0.284 CiviliansDensity 251.000 +/- 152.846 B_Ph_Arty 4102.000 +/- 2619.401 Concealment 0.390 +/- 0.235 B_Ph_AntiTank 4141.000 +/- 2771.929	6 MeanFER 1.286 +/- 0.188 MeanBlueCas 178.700 +/- 21.082 MeanRedCas 140.700 +/- 12.971 B_Armrhits 7.000 +/- 2.305 B_ArtyFireRate 121.000 +/- 54.500 B_Comms_Lat 517.000 +/- 243.340 R_ArtyRadius 28.000 +/- 13.346 B_IntelSensorLat 527.000 +/- 217.520 R_Ph_SmallArms 5782.000 +/- 2440.916 Concealment 0.620 +/- 0.210 R_Speed 110.000 +/- 49.799 R_CommsLat 503.000 +/- 228.868 B_Speed 105.000 +/- 52.962 B_ObstClearRate 52.000 +/- 32.567 CiviliansDensity 298.000 +/- 171.347 R_Armrhits 6.000 +/- 2.508 B_Ph_SmallArms 4883.000 +/- 3043.367 B_Ph_AntiTank 4883.000 +/- 3029.953 R_ArtyGuns 3.000 +/- 1.593 B_ArtyGuns 6.000 +/- 3.000 Cover 0.480 +/- 0.218 R_Ph_Arty 4649.000 +/- 3108.667 R_Stealth 43.000 +/- 32.496 R_ArtyFireRate 88.000 +/- 61.248 B_ResTime 837.000 +/- 511.633 R_Ph_AntiTank 4493.000 +/- 2991.444 B_Ph_Arty 4063.000 +/- 2493.992 B_ArtyRadius 22.000 +/- 13.361 B_Stealth 41.000 +/- 30.721 R_ResTime 689.000 +/- 431.695
7 MeanFER 1.771 +/- 0.983 MeanBlueCas 218.700 +/- 14.034 MeanRedCas 117.400 +/- 28.023 R_Ph_AntiTank 5782.000 +/- 2976.219 B_Speed 123.000 +/- 51.304 R_Stealth 58.000 +/- 30.158 R_ResTime 998.000 +/- 442.179 R_Armrhits 6.000 +/- 2.655 B_ObstClearRate 54.000 +/- 30.975 B_Stealth 53.000 +/- 29.535 B_Comms_Lat 471.000 +/- 251.044 R_ArtyFireRate 101.000 +/- 60.324 B_IntelSensorLat 457.000 +/- 230.050 R_ArtyGuns 3.000 +/- 1.353 CiviliansDensity 293.000 +/- 179.781 R_ArtyRadius 26.000 +/- 14.528 B_Ph_Arty 4961.000 +/- 2867.581 B_Ph_SmallArms 4922.000 +/- 3017.874 R_Ph_SmallArms 4922.000 +/- 2983.169 B_ArtyFireRate 96.000 +/- 59.453 B_ArtyRadius 24.000 +/- 14.439 R_Ph_Arty 4610.000 +/- 2693.747 B_ArtyGuns 6.000 +/- 3.398 Cover 0.440 +/- 0.245 R_CommsLat 376.000 +/- 259.824 Concealment 0.420 +/- 0.259 B_ResTime 802.000 +/- 570.122 B_Ph_AntiTank 4258.000 +/- 2732.839 R_Speed 82.000 +/- 48.650 B_Armrhits 4.000 +/- 1.635	8 MeanFER 0.728 +/- 0.248 MeanBlueCas 90.200 +/- 40.344 MeanRedCas 133.900 +/- 33.950 B_ArtyGuns 8.000 +/- 2.684 R_CommsLat 580.000 +/- 244.569 B_Ph_AntiTank 6250.000 +/- 2782.246 B_Ph_Arty 5899.000 +/- 2857.947 Concealment 0.650 +/- 0.300 B_Armrhits 6.000 +/- 2.771 Cover 0.660 +/- 0.262 B_Stealth 52.000 +/- 23.610 R_ArtyFireRate 98.000 +/- 53.327 B_Ph_SmallArms 5001.000 +/- 2698.385 CiviliansDensity 288.000 +/- 170.397 R_ResTime 872.000 +/- 406.271 R_Ph_SmallArms 4844.000 +/- 2766.691 R_ArtyRadius 25.000 +/- 11.271 R_ArtyGuns 3.000 +/- 1.215 B_ResTime 886.000 +/- 555.814 B_IntelSensorLat 380.000 +/- 296.459 R_Ph_Arty 4610.000 +/- 2586.271 B_ObstClearRate 45.000 +/- 27.400 B_ArtyRadius 23.000 +/- 14.491 R_Stealth 41.000 +/- 24.411 R_Speed 89.000 +/- 59.850 R_Ph_AntiTank 4493.000 +/- 3135.770 B_Comms_Lat 397.000 +/- 307.091 B_ArtyFireRate 79.000 +/- 46.171 R_Armrhits 4.000 +/- 2.645 B_Speed 52.000 +/- 38.116

10	9
MeanFER 1.179 +/- 0.212	MeanFER 1.120 +/- 0.135
MeanBlueCas 120.900 +/- 32.785	MeanBlueCas 175.400 +/- 18.341
MeanRedCas 101.400 +/- 19.833	MeanRedCas 158.400 +/- 4.537
Cover 0.770 +/- 0.175	R_Ph_Arty 6407.000 +/- 2363.833
Concealment 0.740 +/- 0.129	R_Speed 121.000 +/- 63.463
B_ObstClearRate 59.000 +/- 25.849	B_Armrhits 7.000 +/- 2.197
B_Comms_Lat 506.000 +/- 229.679	B_ResTime 1055.000 +/- 443.052
B_ArtyFireRate 116.000 +/- 56.523	B_ArtyRadius 27.000 +/- 14.571
R_ArtyGuns 4.000 +/- 1.471	R_CommsLat 513.000 +/- 256.769
R_Armrhits 6.000 +/- 2.105	CiviliansDensity 314.000 +/- 167.105
R_Ph_Arty 5547.000 +/- 3281.420	B_Ph_Arty 5430.000 +/- 3025.069
R_ResTime 970.000 +/- 399.604	R_ArtyFireRate 106.000 +/- 57.050
CiviliansDensity 307.000 +/- 157.616	B_IntelSensorLat 492.000 +/- 228.871
B_Armrhits 6.000 +/- 2.183	B_Speed 109.000 +/- 58.854
R_Stealth 52.000 +/- 17.480	B_Comms_Lat 478.000 +/- 280.959
B_Stealth 52.000 +/- 27.253	B_Ph_SmallArms 5235.000 +/- 2948.356
R_CommsLat 489.000 +/- 195.909	R_ResTime 928.000 +/- 557.643
B_Ph_Arty 5235.000 +/- 2849.545	B_ArtyFireRate 102.000 +/- 52.197
B_Speed 103.000 +/- 53.294	B_ObstClearRate 50.000 +/- 27.988
R_Ph_AntiTank 5118.000 +/- 3171.533	R_ArtyGuns 3.000 +/- 1.377
B_IntelSensorLat 446.000 +/- 262.324	B_Stealth 50.000 +/- 29.616
B_Ph_AntiTank 5157.000 +/- 3081.957	B_ArtyGuns 6.000 +/- 3.439
R_ArtyFireRate 96.000 +/- 55.436	R_Ph_SmallArms 4805.000 +/- 3079.926
R_ArtyRadius 25.000 +/- 14.896	R_Stealth 46.000 +/- 24.466
R_Speed 93.000 +/- 59.032	B_Ph_AntiTank 4844.000 +/- 2390.488
B_Ph_SmallArms 4454.000 +/- 2805.997	R_ArtyRadius 25.000 +/- 14.468
B_ArtyGuns 6.000 +/- 3.143	R_Armrhits 5.000 +/- 2.670
B_ResTime 823.000 +/- 581.669	R_Ph_AntiTank 4297.000 +/- 3043.913
B_ArtyRadius 23.000 +/- 14.723	Cover 0.370 +/- 0.236
R_Ph_SmallArms 4141.000 +/- 3421.567	Concealment 0.350 +/- 0.221

Table 12. UO – Cluster Data

B. RIVER CROSSING OPERATIONS (RCO)

Figures 67 and 68 show the U matrix and the Hit map, respectively. Figure 69 shows the locations of the outliers in the respective clusters. Table 13 gives the detailed statistics of the respective clusters.

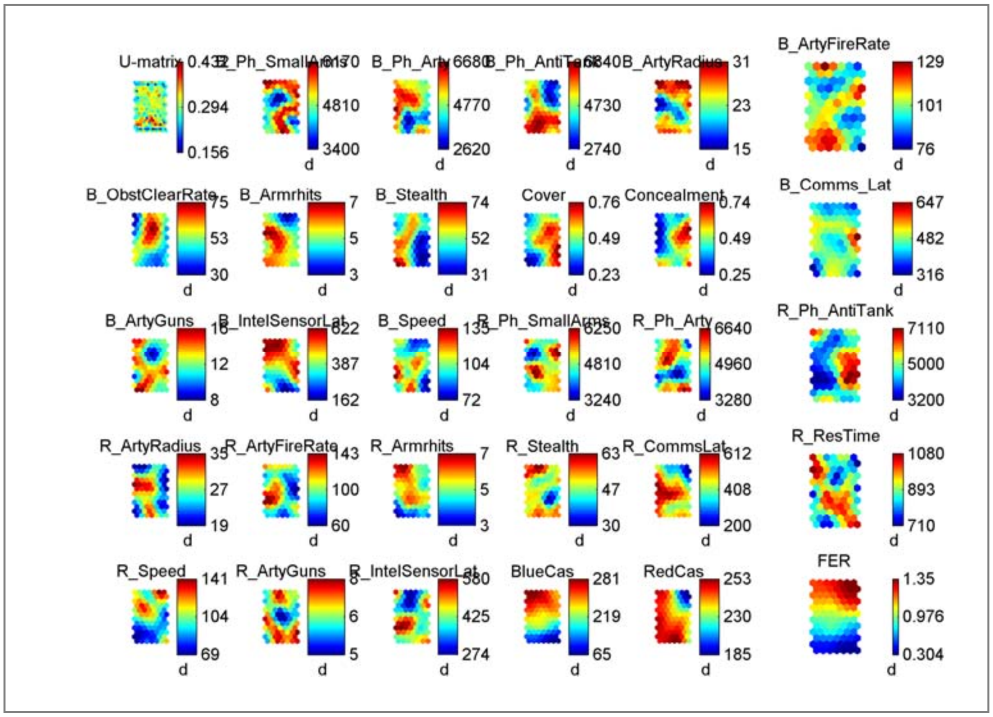


Figure 67. RCO – U-Matrix and Component Planes

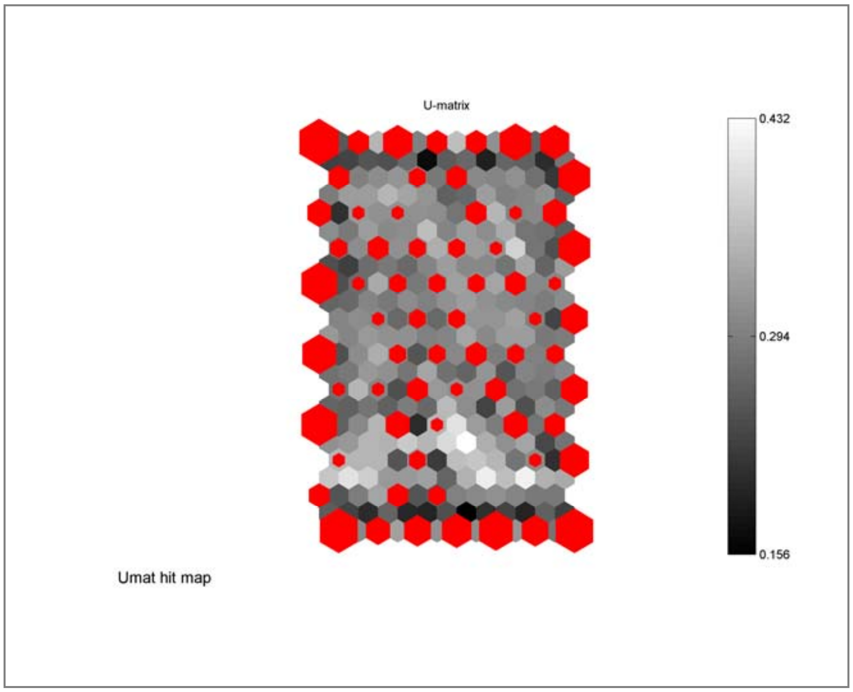


Figure 68. RCO – U-Matrix and Hit Map

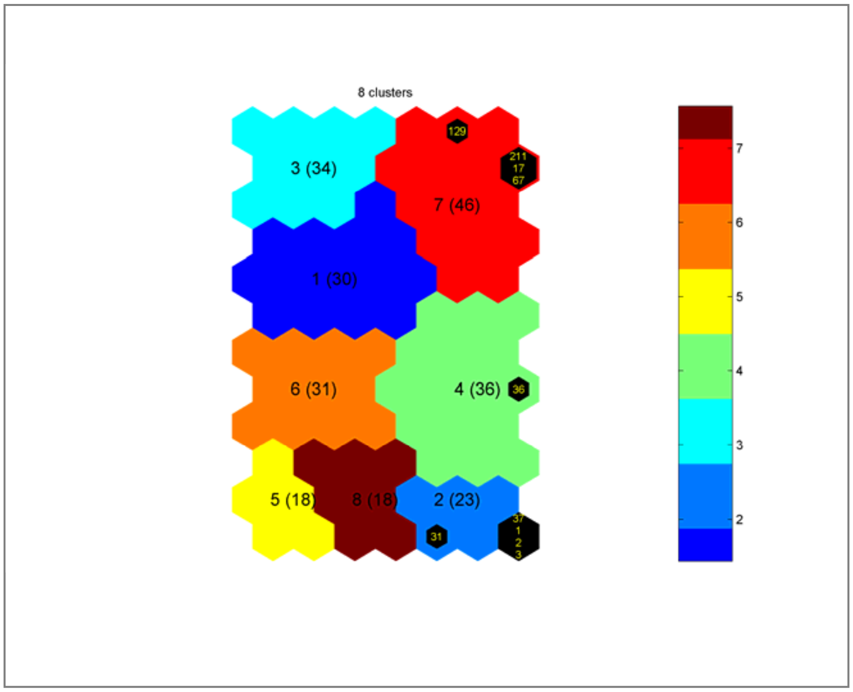


Figure 69. RCO – Cluster and Outlier Map

1 BlueCas 251.000 +/- 23.610 RedCas 241.000 +/- 17.107 FER 1.052 +/- 0.087 R_ArtyRadius 32.000 +/- 11.479 R_Speed 117.000 +/- 52.027 B_Ph_Arty 5977.000 +/- 2786.642 B_IntelSensorLat 520.000 +/- 205.654 B_Armrhits 7.000 +/- 2.063 R_Ph_Arty 5860.000 +/- 2799.317 B_ObstClearRate 61.000 +/- 30.493 R_Armrhits 6.000 +/- 2.315 R_CommsLat 506.000 +/- 282.144 B_Stealth 56.000 +/- 28.108 Cover 0.540 +/- 0.254 R_ArtyFireRate 105.000 +/- 51.325 B_Comms_Lat 485.000 +/- 243.577 B_Speed 104.000 +/- 52.464 R_Stealth 48.000 +/- 29.986 R_ResTime 879.000 +/- 572.881 B_Ph_AntiTank 4688.000 +/- 2956.785 B_ArtyFireRate 98.000 +/- 62.075 B_ArtyGuns 11.000 +/- 6.880 R_ArtyGuns 6.000 +/- 3.342 R_Ph_AntiTank 4415.000 +/- 2709.089 Concealment 0.420 +/- 0.280 B_ArtyRadius 21.000 +/- 11.509 R_Ph_SmallArms 4376.000 +/- 2845.341 R_IntelSensorLat 362.000 +/- 257.328 B_Ph_SmallArms 3985.000 +/- 2393.248	2 BlueCas 85.000 +/- 45.548 RedCas 243.000 +/- 51.898 FER 0.323 +/- 0.192 R_Ph_Arty 6016.000 +/- 2494.370 Cover 0.630 +/- 0.237 R_ResTime 991.000 +/- 466.200 R_ArtyGuns 7.000 +/- 3.044 R_Stealth 54.000 +/- 27.658 R_IntelSensorLat 468.000 +/- 266.140 R_Ph_SmallArms 5274.000 +/- 2483.352 B_Ph_AntiTank 5586.000 +/- 2778.503 B_Ph_Arty 5313.000 +/- 2330.153 Concealment 0.520 +/- 0.301 B_ArtyRadius 26.000 +/- 16.411 R_CommsLat 464.000 +/- 243.492 B_Ph_SmallArms 5118.000 +/- 2921.311 R_ArtyRadius 26.000 +/- 14.933 B_Armrhits 5.000 +/- 2.826 R_Speed 98.000 +/- 59.484 B_ArtyGuns 11.000 +/- 7.154 R_Ph_AntiTank 4532.000 +/- 3009.575 B_Comms_Lat 432.000 +/- 260.874 B_ArtyFireRate 95.000 +/- 59.160 R_ArtyFireRate 87.000 +/- 54.806 R_Armrhits 5.000 +/- 2.810 B_ObstClearRate 42.000 +/- 22.948 B_Speed 88.000 +/- 60.030 B_IntelSensorLat 225.000 +/- 210.997 B_Stealth 35.000 +/- 23.089
3 BlueCas 275.000 +/- 34.399 RedCas 246.000 +/- 9.817 FER 1.138 +/- 0.137 B_IntelSensorLat 612.000 +/- 195.587 R_Armrhits 7.000 +/- 2.293 R_Stealth 59.000 +/- 29.121 B_ArtyRadius 29.000 +/- 15.080 B_Ph_SmallArms 5469.000 +/- 2836.027 B_Ph_Arty 5547.000 +/- 2490.606 R_ResTime 956.000 +/- 538.406 R_Speed 108.000 +/- 48.788 B_ArtyGuns 13.000 +/- 7.059 R_Ph_Arty 5313.000 +/- 2777.764 R_ArtyGuns 7.000 +/- 3.744 B_ArtyFireRate 105.000 +/- 60.292 R_ArtyFireRate 102.000 +/- 63.415 B_Ph_AntiTank 5157.000 +/- 2975.745 R_Ph_AntiTank 4805.000 +/- 3167.771 R_CommsLat 411.000 +/- 233.826 B_Stealth 49.000 +/- 28.234 B_Armrhits 5.000 +/- 1.881 B_Speed 98.000 +/- 59.438 B_Comms_Lat 443.000 +/- 236.218 R_Ph_SmallArms 4610.000 +/- 3274.895 B_ObstClearRate 48.000 +/- 28.181 Cover 0.420 +/- 0.254 R_IntelSensorLat 376.000 +/- 257.706 R_ArtyRadius 23.000 +/- 14.187 Concealment 0.360 +/- 0.237	4 BlueCas 212.000 +/- 63.048 RedCas 240.000 +/- 14.962 FER 0.906 +/- 0.250 R_Ph_AntiTank 6250.000 +/- 2227.190 Cover 0.640 +/- 0.264 Concealment 0.580 +/- 0.217 B_IntelSensorLat 468.000 +/- 249.544 B_ArtyGuns 13.000 +/- 6.592 R_Armrhits 6.000 +/- 2.569 R_ResTime 942.000 +/- 545.644 B_Comms_Lat 492.000 +/- 271.703 R_CommsLat 464.000 +/- 253.441 R_Ph_SmallArms 5118.000 +/- 2678.158 B_Ph_AntiTank 5313.000 +/- 2637.410 B_Ph_SmallArms 5079.000 +/- 2982.239 B_Armrhits 6.000 +/- 2.568 R_IntelSensorLat 415.000 +/- 244.891 B_Speed 100.000 +/- 60.273 B_ObstClearRate 50.000 +/- 28.349 R_ArtyGuns 6.000 +/- 3.562 B_ArtyRadius 22.000 +/- 12.912 B_Ph_Arty 4297.000 +/- 2571.069 R_Speed 91.000 +/- 58.299 B_ArtyFireRate 95.000 +/- 55.559 R_ArtyFireRate 87.000 +/- 59.027 R_ArtyRadius 23.000 +/- 14.166 R_Stealth 40.000 +/- 29.397 R_Ph_Arty 4141.000 +/- 2391.200 B_Stealth 35.000 +/- 26.943
5 BlueCas 133.000 +/- 58.566 RedCas 249.000 +/- 7.086 FER 0.528 +/- 0.238 B_Stealth 69.000 +/- 26.951 B_Ph_AntiTank 6446.000 +/- 2262.377	6 BlueCas 227.000 +/- 29.267 RedCas 247.000 +/- 10.170 FER 0.944 +/- 0.125 R_ArtyFireRate 131.000 +/- 40.942 R_IntelSensorLat 545.000 +/- 233.772

B_ArtyFireRate 116.000 +/- 57.018 B_ArtyGuns 14.000 +/- 6.506 B_Armrhits 6.000 +/- 2.849 R_CommsLat 503.000 +/- 237.146 B_ArtyRadius 27.000 +/- 13.873 Concealment 0.520 +/- 0.202 R_Stealth 51.000 +/- 29.995 B_IntelSensorLat 422.000 +/- 304.042 B_Ph_Arty 4961.000 +/- 2292.559 R_IntelSensorLat 432.000 +/- 221.962 B_Speed 104.000 +/- 65.679 B_ObstClearRate 53.000 +/- 31.527 R_Ph_Arty 4922.000 +/- 2873.673 R_ArtyFireRate 95.000 +/- 58.763 B_Ph_SmallArms 4649.000 +/- 3062.647 R_Ph_AntiTank 4532.000 +/- 3325.646 R_ArtyGuns 6.000 +/- 3.092 R_Ph_SmallArms 4376.000 +/- 2400.096 R_ResTime 823.000 +/- 569.757 B_Comms_Lat 383.000 +/- 287.544 R_ArtyRadius 21.000 +/- 13.372 R_Armrhits 4.000 +/- 2.579 Cover 0.260 +/- 0.181 R_Speed 72.000 +/- 39.067	R_CommsLat 559.000 +/- 206.622 R_Ph_SmallArms 5704.000 +/- 2744.418 B_Stealth 60.000 +/- 24.246 B_Speed 114.000 +/- 54.811 B_Armrhits 6.000 +/- 2.486 R_ArtyRadius 28.000 +/- 14.974 B_ObstClearRate 57.000 +/- 27.294 R_Armrhits 6.000 +/- 2.550 B_Ph_AntiTank 5508.000 +/- 3014.905 R_ResTime 942.000 +/- 515.091 B_ArtyFireRate 106.000 +/- 55.926 R_ArtyGuns 7.000 +/- 3.076 R_Stealth 50.000 +/- 25.879 B_Ph_SmallArms 5001.000 +/- 2899.274 B_ArtyGuns 12.000 +/- 6.736 B_Comms_Lat 471.000 +/- 247.789 B_Ph_Arty 4805.000 +/- 3264.273 Cover 0.480 +/- 0.299 B_IntelSensorLat 355.000 +/- 242.410 R_Speed 92.000 +/- 59.747 B_ArtyRadius 22.000 +/- 12.992 R_Ph_Arty 4532.000 +/- 2814.683 Concealment 0.370 +/- 0.226 R_Ph_AntiTank 3633.000 +/- 2497.540
7 BlueCas 254.000 +/- 42.210 RedCas 209.000 +/- 49.309 FER 1.223 +/- 2.067 B_ArtyRadius 29.000 +/- 13.299 R_Speed 113.000 +/- 56.263 Cover 0.590 +/- 0.283 B_Ph_SmallArms 5391.000 +/- 2657.256 R_Ph_SmallArms 5352.000 +/- 2950.857 B_ObstClearRate 59.000 +/- 30.402 Concealment 0.540 +/- 0.294 B_IntelSensorLat 464.000 +/- 226.833 R_Ph_AntiTank 4883.000 +/- 2807.337 R_Stealth 49.000 +/- 28.894 B_Ph_Arty 4922.000 +/- 2934.563 R_Ph_Arty 5118.000 +/- 2965.816 R_ArtyGuns 6.000 +/- 2.870 R_Armrhits 5.000 +/- 2.503 B_ArtyFireRate 101.000 +/- 58.012 B_Stealth 50.000 +/- 27.135 R_IntelSensorLat 408.000 +/- 269.562 B_Comms_Lat 446.000 +/- 262.682 R_ResTime 844.000 +/- 544.525 B_Speed 93.000 +/- 53.598 B_ArtyGuns 11.000 +/- 6.376 R_ArtyFireRate 86.000 +/- 56.040 R_ArtyRadius 23.000 +/- 12.325 R_CommsLat 323.000 +/- 257.642 B_Armrhits 4.000 +/- 2.679 B_Ph_AntiTank 3321.000 +/- 2430.416	8 BlueCas 139.000 +/- 67.397 RedCas 250.000 +/- 12.683 FER 0.548 +/- 0.273 B_Ph_AntiTank 6641.000 +/- 2645.964 B_ArtyFireRate 119.000 +/- 53.514 R_ArtyGuns 7.000 +/- 2.859 R_ArtyRadius 30.000 +/- 11.587 B_Speed 119.000 +/- 49.704 B_Ph_SmallArms 5586.000 +/- 2967.950 B_ArtyGuns 14.000 +/- 6.231 R_Stealth 54.000 +/- 29.570 B_Armrhits 6.000 +/- 2.238 B_ArtyRadius 26.000 +/- 15.628 B_Comms_Lat 499.000 +/- 269.247 R_IntelSensorLat 450.000 +/- 261.830 R_Ph_Arty 5235.000 +/- 3449.621 B_Stealth 53.000 +/- 27.912 Concealment 0.480 +/- 0.282 R_CommsLat 425.000 +/- 254.235 R_Ph_SmallArms 4844.000 +/- 3048.396 R_ResTime 865.000 +/- 506.741 R_Ph_AntiTank 4454.000 +/- 3410.422 R_ArtyFireRate 88.000 +/- 40.152 R_Armrhits 5.000 +/- 2.526 B_ObstClearRate 45.000 +/- 28.114 Cover 0.370 +/- 0.245 B_IntelSensorLat 253.000 +/- 146.142 B_Ph_Arty 3555.000 +/- 2482.486 R_Speed 78.000 +/- 62.549

Table 13. RCO – Cluster Data

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX D. INTERNATIONAL DATA FARMING WORKSHOP 17 TEAM REPORT

The thesis is presented in International Data Farming Workshop 17, held in Garmisch, Germany from 21 Sep 08 – 26 Sep 08. Additional work was done on exploring the tactics, techniques and procedures (TTPs) of the defender operating in an Urban Terrain. Essentially it is a manual red teaming effort to gain insights on how the defender should locate his static forces and how the defender should deploy his reinforcements.

TEAM 5 MEMBERS

CPT CHER HOWE, ONG
Naval Postgraduate School, USA/Singapore

CPT WEE CHUNG, SIM
Republic of Singapore Navy, Singapore

KURT GRAU
IABG, Germany

INTRODUCTION

Modern warfare is characterized by the use of combined arms where various types of forces come together to fight as a single entity, as a system-of-systems. Typically, for land forces, system-of-systems are battalion level and above. In this workshop, the terrain that was selected to be studied is the urban terrain. The team's objective was to explore the tactics, techniques and procedures (TTPs) of the defender operating in an urban terrain. The specific aim was to determine how the defender should locate his defensive positions and also how he should deploy his reserves. The scenario map was developed by the DSO National Laboratories, Singapore.

DESCRIPTION OF SCENARIO

The scenario examined during the workshop was a battalion attack of a company plus defended urban locality. The defender deploys a section and a platoon plus of mechanized infantry at the forward positions each along the 3 main axes. A company minus sized mechanized infantry reserve organized into 2 echelons is held at the rear to reinforce the forward positions. The entire defense is supported by a mortar platoon providing support fire. The green rectangles are obstacles emplaced in the defended locality. The defender's defense is as shown in Figure 1 below:

Figure 1: Defense Plan

The attacker inserts a platoon sized block force to the depth and advances along 2 axes with a company of mechanized infantry each, holding a company minus mechanized infantry as the reserve that will be activated upon breaking through either axes. The attack is supported by an artillery battery and a UAV. The attack plan is as shown in Figure 2.

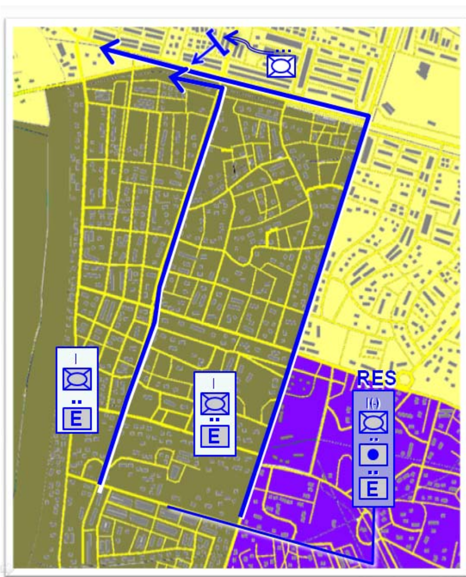


Figure 2: Attack Plan

DESIGN OF EXPERIMENTS

For the defensive positions, 3 concepts are studied:

- Forward – This is where the defender pushes all his static forces to the front positions.
- Depth – This is where the defender locates all his forces at the rear of the operating area.
- Mixed – The defender deploys his forces uniformly along the axes.

For the reinforcement routes, 3 concepts are studied:

- No reserve – No reserves, all forces are deployed at the static defense positions.
- Frontal – The reserves are deployed "head-on" with the direction of the attacker.
- Flanking – The reserves comes from the flanks of the attacker.

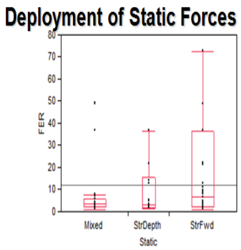
Figure 3 shows how the defender deploys his forces according to the concepts mentioned above:

Figure 3: Design of Experiments – Defender Concepts of Defense

These various combinations of static forces and reserves make up for a total of 3x3 = 9 combinations of tactics that the defender can employ. A total of 10 replicates are made for each of the combination of static and reserve employment concept.

RESULTS

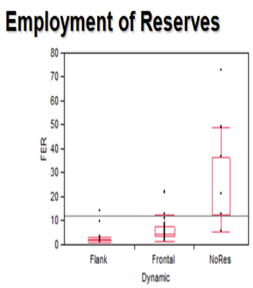
From Figure 4 below, we can see that a mixed deployment strategy produces the smallest mean Force Exchange Ratio. In addition, from the box plot in Figure 4, we can see that the variation of outcome for a mixed deployment strategy is the smallest among the 3 concepts.



	No Reserves	Flanking Maneuver	Frontal Maneuver
Strong Forward	1	4	7
Strong Depth	2	5	8
Mixed	3	6	9

Figure 4: Analysis for deployment of static forces

From Figure 5 below, we can see that deploying reserves to the flanks of the attacker produces the smallest mean Force Exchange Ratio. In addition, the variation of the battle outcome for a flanking maneuver is also the smallest.



	No Reserves	Flanking Maneuver	Frontal Maneuver
Strong Forward	1	4	7
Strong Depth	2	5	8
Mixed	3	6	9

Figure 5: Analysis for deployment of reserves.

From Figure 6 below and together with the analysis done previously, we can see that employing a mixed deployment strategy and deploying the reserves to the flanks of the attacker is the most optimal and also robust combination for the defender in the urban terrain.

	No Reserves	Flanking Maneuver	Frontal Maneuver
Strong Forward	1	4	7
Strong Depth	2	5	8
Mixed	3	6	9

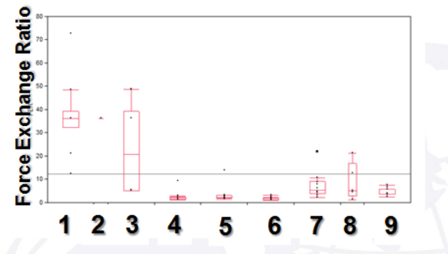


Figure 6: Combined Analysis

CONCLUSION

The results obtained from workshop provided interesting insights on how tactics and doctrine can be evaluated and validated using data farming techniques. The results suggest that for the defender, the best tactic would be to spread his forces along main axes of movement and have the reserves reinforce from the flanks of the attacker. By spreading his forces along the main axes, he would be able to reduce his vulnerability to the attacker's artillery fires. In addition, by deploying his reserves from the flanks, the defender would be able to avoid a head-on fire fight with the attacker. The reserves would engage in decisive combat with the attacker only when they arrive at the position to be reinforced.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Allied crossings of the Rhine north of the Ruhr. (n.d.). Retrieved October 16, 2008, from http://www.onwar.com/maps/wwii/westfront/rhine45a.htm: 2008.

Choo, C. S., Chua, C. L., & Tay, S.-H. V. (2007). Automated red teaming: A proposed framework for military applications. *Proceedings of the 9th annual conference on genetic and evolutionary computation.*

Choo, C. S., Ng, E. C., & Chua, C. L. (n.d.). Clustering and outlier analysis for data mining (COADM). *Scythe Issue 3 Workshop 15 page 34*.

Cioppa, T. M. (2002). *Efficient nearly orthogonal and space-filling experimental designs for high-dimensional complex models.* Naval Postgraduate Master's Thesis.

Cioppa, T. M., Lucas, T. W., & Sanchez, S. M. (2004). Military Applications of Agent Based Simulations. *Proceedings of the 2004 Winter Simulation Conference* .

DSTA. (2003, December 29). *DSTA in the news*. Retrieved Oct 01, 2008, from DSTA in the news: http://www.dsta.gov.sg/index.php?option=com_content&task=view&id=3130&Itemid=401.

Headquarters, Department of the Army. (2003). *Field Manual 3-06 Urban Operations.* Retrieved October 16, 2008, from Global Security: http://www.globalsecurity.org/military/library/policy/army/fm/3-06/index.html.

Headquarters, Department of the Army. (1998). *Field Manual 90-13 River Crossing Operations.* Retrieved October 16, 2008, from Global Security: http://www.globalsecurity.org/military/library/policy/army/fm/90-13/.

Headquarters, Department of the Army. (2001, July 4). *Field Manual 3-90 Tactics.* Retrieved October 1, 2008, from Global Security: http://www.globalsecurity.org/military/library/policy/army/fm/3-90/ch9.htm.

Joint Chiefs of Staff, United States. (2006). *Joint Publication 3.0 Joint Planning.* Retrieved Oct 16, 2008, from http://www.dtic.mil/doctrine/jel/new_pubs/jp3_13_3.pdf.

McIntosh, G. C., Galligan, D. P., Anderson, M. A., & Lauren, M. K. (2007). *MANA (map aware non-uniform automata) user's manual.* Operations Analysis Section, Defense Technology Agency.

Sulewski, C. A. (2005). *An exploration of unmanned aerial vehicles in the army's future combat systems family of systems.* Naval Postgraduate School Master's Thesis.

Team 7 – Applying Automated Red Teaming in an Urbans Operations Scenario. (2007). *Scythe: Proceedings and Bulletin of the International Data Farming Community Issue 1 - Workshop 13*.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Professor Thomas W. Lucas
   Naval Postgraduate School
   Monterey, California

4. Mr. Chwee Seng Choo
   DSO National Laboratories
   Singapore

5. Professor Tat Soon Yeo
   Director, Temasek Defense Systems Institute (TDSI)
   National University of Singapore
   Singapore

6. Tan Lai Poh (Ms), Assistant Manager
   Temasek Defence Systems Institute
   National University of Singapore
   Singapore

7. Captain Cher Howe Ong
   Singapore Armed Forces
   Singapore

8. LTC Hudak
   TRAC-MTRY
   Monterey, California